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...from Tank

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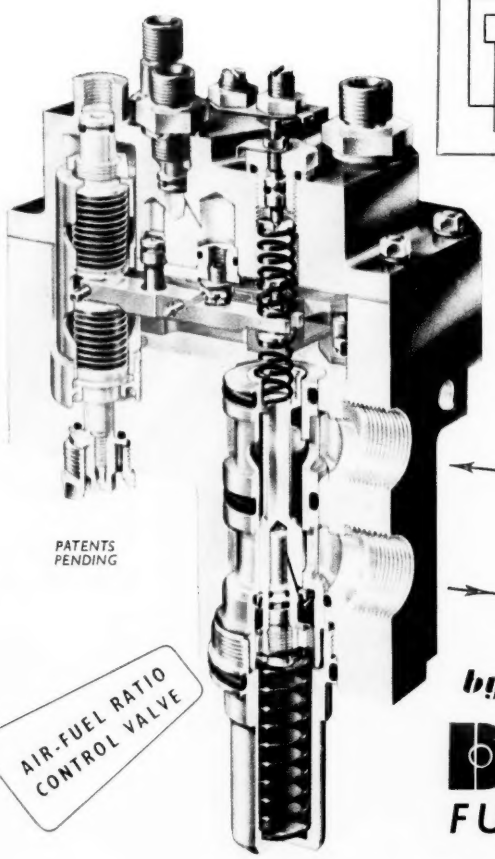

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Secretary's News Letter

SEPTEMBER 1952

WHEN the Lecture Programme for 1952-1953 is published, it will be seen that the number of Main Society Lectures has been reduced. The Council have decided that in future years there will be three to five Main Lectures held in London (excluding the Bleriot, the Wilbur Wright and the British Commonwealth and Empire Lectures) and three/four held at the Branches.

During the next Session the three Branches at which will be delivered the Main Lectures will be Weybridge (in November), Derby (in February) and Glasgow (in April). At Weybridge Sir Roy Fedden is to give the first Rex Pierson Memorial Lecture which the Branch have founded.

The Society's Library receives many Reports issued both at home and abroad and these are listed each month in the " Additions to the Library " section at the end of the Journal. Hitherto these Reports have been listed under the names of the authorities responsible for their publication, such as the Aeronautical Research Council. This month it will be noticed that they have been classified under major headings, such as Aerodynamics, Structures and Materials. It is hoped that this new classification will prove to be more useful to members than the previous method.

A happy photograph taken at Nast Hyde, Hatfield, where Major and Mrs. Halford entertained the staff of the Society to lunch following their visit to the de Havilland works on 14th August —altogether a most enjoyable occasion, greatly appreciated.

The Scholarship Selection Board has interviewed candidates for the Scholarships administered by the Society, namely the Geoffrey de Havilland, the Charter, and the Busk. This is the first award to be made since the Society took over the administration of the Busk Studentship. The list of previous holders of the Busk contains not a few names, now well-known in aviation, and I hope to say something of them in a future News Letter.

On Thursday 14th August, at the invitation of the Immediate Past President, Major Frank Halford, the staff of the Society visited the de Havilland Works at Hatfield. This was the fulfilment of an invitation of long standing; the delay was due to the illness of Major Halford. Anticipation may sometimes be better than realisation, but certainly not in this case. The ladies discovered another use for hydrogen peroxide, somewhat noisier than the accustomed use. They now talk learnedly of jigs and test-beds. To most the highlight of the day was the trip in the Heron. "The Flight of the Heron" is no longer a book title to the staff; it will now recall memory of an aeroplane flight made under ideal conditions.

Members of the Society will be pleased to know that Major Halford is making good progress. He is looking better and feeling better, although perhaps not quite at the top of his bent.

A. M. Ballantyne

Secretary

NOTICES

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(*An annual sum of £250 is available for premium awards for papers published in the Journal. These premium awards are usually 15 guineas each. Members and non-members of the Society are invited to submit papers on any aspect of aeronautics.*)

HONOURS

Mr. B. N. Wallis, C.B.E., F.R.S., *Fellow*, will have the Honorary Degree of D.Sc.(Eng.) in the University of London conferred on him when the University celebrates Foundation Day on Friday 28th November 1952.

DIARY

LONDON.

October 2nd.

EIGHTH BRITISH COMMONWEALTH AND EMPIRE LECTURE. Maintaining Airworthiness in Operation. R. E. Hardingham, O.B.E., F.R.Ae.S. **Institution of Mechanical Engineers,** Storey's Gate, S.W.1, at 6 p.m. (Tea at 5.30).

BRANCHES.

September 10th.

Brough—Lecture by an American on Production Methods in the U.S.A. Electricity Showrooms, Ferensway, Hull. 7.30 p.m. Admission by ticket only.

September 16th.

Glasgow—Response Calculations. Professor W. J. Duncan. Royal Technical College. 7.30 p.m.

September 17th.

Coventry—Aerofoil Sections and their Derivation. E. T. B. Smith. The Wine Lodge. 7.30 p.m.

MEMBERS' NEW APPOINTMENTS

R. P. CASTLE (*Graduate*), formerly of A. V. Roe (Canada) Ltd., has been appointed Design Engineer with the Consolidated Vultee Aircraft Corporation at San Diego.

A. R. DARE (*Graduate*), formerly with Vickers-Armstrongs Ltd., is joining the Design Office of Canadair Ltd., Montreal.

M. J. EDMONDS (*Associate Fellow*), formerly with British Overseas Airways Corporation, has been appointed Quality Engineer with Rolls-Royce Ltd. at their East Kilbride Factory.

GERALD C. FREWER (*Associate*), previously with A. V. Roe (Canada) Ltd., has joined the Republic Aviation Corporation of Long Island as a Class A Designer.

F/LT. A. F. HINDELL (*Associate*) has been seconded to the Royal Ceylon Air Force for Technical Duties.

J. H. LOWDEN (*Associate Fellow*), formerly Chief Designer of the Special Projects Division at Salisbury, South Australia, has recently joined the Production Staff of Chrysler Australia Limited (Aircraft Division), Finsbury, South Australia.

R. J. MCWILLIAMS (*Associate*) has been appointed Assistant Chief Engineer of Canadian Pacific Air Lines Limited.

N. H. PAYNE (*Associate Fellow*), previously Chief Development Engineer, de Havilland Engine Co., has been appointed Chief Engineer, Normalair Ltd., Yeovil.

S. SPEIGHT (*Associate*), formerly Technical Investigating Engineer with the Project and Development Section of British European Airways, has been appointed Liaison Engineer with the Graviner Manufacturing Company, Colnbrook.

CIERVA MEMORIAL PRIZE 1951-1952

The Cierva Memorial Prize for 1951-1952 has been awarded by the Council of the Helicopter Association of Great Britain to L. H. Hayward for his paper "A Review of Helicopter Patents." The paper was given before the Helicopter Association during the 1951-52 Lecture Session and a reprint was issued with Vol. 5, No. 4, of the Journal of the Helicopter Association.

INSTITUTION OF ELECTRICAL ENGINEERS

Members of the Society are invited to attend a lecture on "Radio Telemetering" to be given before the Radio Section of The Institution of Electrical Engineers by E. D. Whitehead, M.B.E., B.Sc., A.M.I.E.E., and J. Walsh, B.Sc. The lecture will be held in the Lecture Theatre of the Institution at 5.30 p.m. (tea at 5 p.m.) on Wednesday 12th November 1952.

ELECTIONS

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

Carlo F. Bona
Romesh Chandra Manocha (*from Associate*)
Thomas Alan Stenning

Associates

Herbert Arthur Ernest Brett
Leslie George Albert Brister
Eric William Lamb
Ernest George Douglas Lancaster
Stanley Livingston
Douglas Augustine Patterson
Wladyslaw Zielinski

Graduates

Arthur George Debbage
John Finbarr Ogle
William Dennis Sproson (*from Student*)

Student

Harijs Raimonds Kruza

Companion

Cyril William Cleverdon

MEMORIAL TO SIR JOHN ALCOCK AND SIR ARTHUR WHITTEN BROWN

TO BE DONATED BY "THE BRITISH AERONAUTICAL COMMUNITY"

The following letter of Appeal has been issued in connection with the plan for a Memorial to Sir John Alcock and Sir Arthur Whitten Brown:

Nearly 33 years ago two Englishmen, Sir John Alcock and Sir Arthur Whitten Brown made their historic first direct flight across the Atlantic.

It has been thought fitting that a worthy and permanent Memorial should be erected to commemorate the two courageous airmen who embarked upon that flight in full knowledge of its hazards, and brought it to a successful issue.

The Royal Aero Club, in collaboration with the other leading British aeronautical organisations, has undertaken to launch an appeal to members of the British Aeronautical Community for funds to make this possible, and invites your support.

John Alcock (pilot) and Arthur Whitten Brown (navigator) made that first direct Atlantic flight during the night of 14-15th June 1919 in a Vickers Vimy bomber, fitted with two 350 h.p. Rolls-Royce Eagle engines. The start was made from St. John's, Newfoundland, and some 16 hours 12 minutes later the landing was made at Clifden, County Galway, Ireland. The distance of 1,950 miles had been covered at an average speed of about 120 m.p.h.

Today, multi-engined airliners carrying up to 60 passengers are constantly crossing the Atlantic at speeds of 300 m.p.h. or more, and still higher speeds are in sight, but the courage of Alcock and Brown in embarking on their historic flight is accentuated by the limited performance of their aircraft and the complete lack of navigational aids then available to them.

It is felt that no more suitable location for a Memorial to Alcock and Brown could be found than the site of the new Terminal Building at London Airport, where it would be seen by the thousands of passengers departing for or arriving from their Atlantic or other long-distance voyages. An admirable position has been allocated by the Ministry of Civil Aviation, and with sufficient support the Memorial can be completed and erected in time for the opening of the new Terminal Buildings.

The design of the Memorial, in the form of a group statue of the two men, has been entrusted to Mr. William McMillan, R.A., who is working in co-operation with the Architect of London Airport to ensure that the Memorial will be in harmony with its surroundings.

We are confident it will be generally recognised that the proposed Memorial is worthy of enthusiastic and generous support. Donations should be sent to:

The Secretary-General, The Royal Aero Club,
119 Piccadilly, London, W.1.
and cheques should be crossed "Alcock/Brown Memorial Fund."

(Signed) BRABAZON OF TARA,
President,
The Royal Aero Club of the United Kingdom.

(Signed) GEORGE DOWTY,
President,
The Royal Aeronautical Society.

(Signed) PHILIP JOUBERT DE LA FERTÉ,
Deputy-President,
The Air League of the British Empire.

(Signed) J. LANKESTER PARKER,
Master,
Guild of Air Pilots and Air Navigators of the British Empire.

Fuel Systems for Turbine-Engined Aircraft

by

J. E. WALKER, A.F.R.Ae.S.

The 855th Lecture to be given before the Royal Aeronautical Society, "Fuel Systems for Turbine-Engined Aircraft" by Mr. J. E. Walker, A.F.R.Ae.S., was read under the auspices of the Luton Branch of the Society on the 24th April 1952 at Luton.

Mr. F. S. Lester, Chairman of the Luton Branch, welcomed the many visitors, particularly Mr. G. H. Dowty, F.R.Ae.S., Vice-President and President-Elect of the Society, and the Secretary, Dr. A. M. Ballantyne, T.D., A.F.R.Ae.S.

Mr. G. H. Dowty, F.R.Ae.S., who presided for the rest of the meeting, apologised for the absence of the President who was prevented from attending by ill health. He was sure they would wish him to convey to the President their wishes for his speedy restoration to health.

The present meeting was notable because it was the first main lecture to be read before the Luton Branch. Although the Branch was in close proximity to London—rather more so than most—they were holding this lecture there because it was the tenth anniversary of the founding of the Branch. He brought from the Council very sincere congratulations on completing their ten years and good wishes for the future. As Vice-President he had visited a number of branches in recent months and had been struck by the great enthusiasm that prevailed among them. That, he thought, was largely due to the good work of the local officers and the Branches Committee of the Society, and to the hard working Chairman, Mr. N. E. Rowe, whom he was glad to see was present.

It was interesting to note that there were present representatives from six other Branches, including Gloucester and Cheltenham, Hatfield, Coventry and Preston. He thought it showed great keenness that members from Branches so far away should attend this lecture.

He had pleasure in introducing the Lecturer, Mr. J. E. Walker, Chief Power Plant Engineer of the de Havilland Aircraft Co. Ltd. Mr. Walker was also Chairman of the Hatfield Branch.

INTRODUCTION

The title of this paper suggests that fuel systems for turbine-engined aircraft are fundamentally different from those of other aircraft. This is not entirely the case and much of the material of this paper applies to aircraft using piston engines. Turbine engines, however, make more exacting demands in certain aspects, while considerable relief is provided by the use of less volatile fuels. To keep the paper as objective as possible, turbine-engined aircraft requirements only have been considered.

The paper is divided into four sections —Section 1 reviews briefly those characteristics affecting fuel system design of the two main turbine engine fuels—Kerosine and Wide-Cut Gasoline of 2 to 3 lb./in.^{2} Reid Vapour Pressure (R.V.P.). More volatile gasolines, while capable of being used in turbine engines, are not specifically catered for in turbine-engined aircraft design, and if they are used as an expedient it will be with limitations on fuel system performance.

The literature on fuels is comprehensive and nothing new is given in this section, but it was necessary to review the bare essentials for a clearer understanding of the material which follows.

Section 2 discusses some aspects of Detail Design of items used in Fuel Systems and has been introduced to illustrate certain points which it is hoped will be of value.

Section 3 discusses the underlying principles of Fuel System Design. The engine fuel system has not been included since it is outside the scope of the aircraft designer, and has become a specialised branch of development in its own right. The paper therefore deals with the Low Pressure Aircraft System as distinct from the High Pressure Engine System.

Section 4 discusses methods of Test and Test Equipment and gives some results of high altitude flight tests with the Comet.

1. CHARACTERISTICS OF FUELS FOR TURBINE ENGINES

Those characteristics affecting fuel system designs of the two main turbine engine fuels are given in Fig. 1, which has been compiled from information available at the time.

Some of the data is not controlled by the specification reference given.

Kerosine or Paraffin is universally known. Wide-Cut Gasoline is a fuel of medium vapour pressure (2-3 lb./in.² R.V.P.) which has been devised to minimise the difficulties in fuel system design in dealing with fuel that boils too readily, while at the same time utilising as wide a range of the constituents of the crude oil as possible.

The repercussions of these characteristics on aircraft and their fuel systems will be considered briefly.

1.1. Specific Gravity and Heat of Combustion

A major problem in aircraft design is to provide for sufficient fuel tank capacity and, since range depends upon the number of Heat Units which can be carried, it is an advantage to have a fuel giving the greatest heat value per unit volume. This does not necessarily apply when operating an aircraft with maximum capacity useful load on a route stage of shorter distance than the maximum range; that is where useful load is displaced by fuel weight.

Assuming a constant heating value per pound of fuel, and taking kerosine at 15°C. as a standard of comparison, the use of wide-cut gasoline with its large manufacturing tolerances on specific gravity may involve range-losses as follows:—

Wide-Cut Gasoline of lowest specific gravity,

at 15°C., reduces range by at least 7 per cent.

at 40°C. reduces range by at least 10 per cent.

Figure 2 gives these effects in more detail.

1.2. Vapour Pressure

The tendency to Vapour Evolution, for comparative purposes, is measured as Reid Vapour Pressure (R.V.P.) at a fuel temperature of 100°F.

Knowledge, or vapour pressure, has assisted the designer of a fuel system in evaluating its performance and is a key factor in dealing with high altitude effects, since it reveals the temperature and pressure conditions at which the fuel will boil. This must be kept continually in mind when designing a fuel system since restrictions, such as pipe unions, sharp bends, and so on, raise the flow velocity locally and lower the pressure, causing vapour release in the feed line where it can do much harm because it cannot escape.

It will be seen from Fig. 3 that Wide-Cut Gasoline with a Reid Vapour Pressure of 3 lb./in.², which is low compared with piston engine fuels of 7 lb./in.², can still lead to trouble. On the other hand kerosine removes all anxiety in this respect. The tendency for any fuel to boil can be suppressed by tank pressurisation, but this must involve additional tank strength and weight and the installation of pressure control units which, if they fail to work, may lead to dangerous trouble through over-pressurisation or restriction to inward venting.

Figure 4 shows diagrammatically a rig which was made to fit into an altitude chamber to demonstrate some of these effects. It consists of two transparent containers, one of which is fitted with an immersed booster pump. The fuel runs by gravity from the large container through the lower pipe line to the small container. From this container it is pumped via the upper transparent pipe through the flow meter and then passes through a pipe to the outside of the altitude chamber, where a flow control cock is fitted. The fuel then re-enters the chamber and is passed back to the larger container. Both containers are vented to the altitude chamber.

Fuel	*Fuel temp. °C.*	*Specific gravity*	*Range loss %*	*Range gain %*
Kerosine	15	0.80 Normal	—	—
„ „	15	0.79 Minimum	1.25	—
„ „	15	0.83 Maximum	—	1.3
„ „	40	0.782 Normal	2	—
Wide-cut Gasoline	15	0.78 Average	2	—
„ „	15	0.739 Minimum	7	—
„ „	15	0.825 Maximum	—	1.4
„ „	40	0.77 Average	3	—
„ „	40	0.739 at 15°C.	10	—

Fig. 2. Effect of specific gravity on range.

	AVIATION KEROSINE	WIDE CUT GASOLINE
SPECN {TYPE TEST FUEL / NORMAL BULK} CURRENT AMERICAN EQUIV.	DERD/2482 MIL-F-5616 J.P.1.	RDE/F/KER/210 DERD/2486 MIL-F-5624A J.P.4.
1. SPECIFIC GRAVITY 60°F	0·80 NORMAL ⊗ 0·79 – 0·83 RANGE	0·78 AVERAGE 0·739 – 0·825 RANGE
2. HEAT OF COMBUSTION	18,500 B.T.U./LB. WT. 147,000 B.T.U./IMP.GALL.	18,700 B.T.U./LB.WT. 143,500 B.T.U./IMP.GALL.
3. COEFF. OF VOL EXPN.	0·00094 PER °C	0·00094 – 0·00120 PER °C
4. R.V.P.	0·12 P.S.I.	2 – 3 P.S.I.
5. DISSOLVED AIR (I) (SEA LEVEL EQUILIBRIUM)	14% BY VOLUME (VOL. OF AIR/VOL. FUEL)	14 – 24% BY VOLUME
6. DISSOLVED WATER	·006% BY WEIGHT AT 20°C ·026% BY WEIGHT AT 50°C	·007% BY WEIGHT AT 20°C ·028% BY WEIGHT AT 50°C
7. FREEZING POINT (INITIAL)	−40°C MAX.	−60°C MAX.
8. FLASH POINT	+ 38°C (MIN.)	− 23 °C (3 P.S.I. R.V.P) − 14 °C (2 P.S.I. R.V.P.)
9. SPONTANEOUS IGNITION TEMP. (II)	650 °C OPEN STEEL PLATE 200-238°C 6" STEEL TUBE ⊗	650 – 720 °C OPEN ⊗ STEEL PLATE
10. RATE OF FLAME PROPAGATION (III)	4 FT./SEC. (APPROX.) AT FUEL TEMPS. GREATER THAN 38°C	4 FT./SEC. (APPROX.) AT FUEL TEMPS. GREATER THAN −23°C
11. AROMATICS	20% BY VOLUME (MAX.)	25% BY VOLUME (MAX.)
12. SULPHUR CONTENT	0·2% BY WEIGHT (MAX.)	0·4% BY WEIGHT (MAX.)
13. KINEMATIC VISCOSITY	6CS. AT 0°F (MAX.)	2·0 CS. AT 0°F (MAX.)

⊗ – NOT IN SPECIFICATION

NOTES:

(I) THE AIR DISSOLVED IN FUELS IS SLIGHTLY OXYGEN RICH.

(II) THESE ARE COMPARATIVE ONLY. THE VALUE DEPENDS MUCH ON METHOD OF TEST.

(III) FLAME WILL NOT PROPAGATE AT FUEL TEMPERATURES BELOW LOWER LIMIT OF INFLAMMABILITY. I.E. AT SEA LEVEL, THE FLASH POINT.

Fig. 1. Turbine engine fuel data.

Figure 5 shows the rig in action at ground level pressure. Wide-Cut gasoline is being used, pre-heated to 56°C., and the tank pump is circulating the fuel at a rate of about 3,500 lb. per hour and 9 lb./in.² delivery pressure.

The rate of flow was adjusted slightly during this test to prevent the small container emptying.

Figure 6 shows the same rig at an altitude of 40,000 ft. which was just below the boiling altitude of the fuel. The line restrictor in the gravity feed pipe can be seen to be causing vapour release from the fuel on the down-stream side. The frothing in the small container is caused by vapour and air release at the pump impeller. This vapour is guided

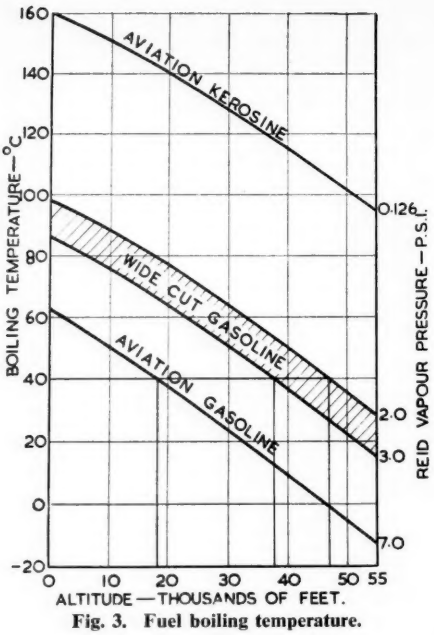

Fig. 3. Fuel boiling temperature.

clear of the ingoing fuel by the vapour guide cone on the pump. Additional sleeving, which is normally fitted, provides even better separation but was removed in these tests for visual clarity.

Figure 7 shows the altitude of the chamber raised to 45,000 ft. where the fuel is boiling. There are a few bubbles passing down the gravity feed line and the restrictor is causing considerable vapour formation. The fuel in the pump container is boiling violently, but the pump delivery is clear and the flow is maintained. The delivery pressure, however, has, dropped to 6 lb./in.^{2}.

When the altitude of the chamber was raised above 45,000 ft. fuel froth spouted out of the tank vents violently, causing severe loss of fuel.

1.3. Air release from fuel

Air is soluble in all fuels and is released from the fuel during the climb and the initial cruising periods of flight.

The amount of air is relatively small and provided that it is released in the fuel tanks it will not affect the fuel feed. If, however, it is released in the feed pipe by some sharp-edged restriction, as shown in Fig. 6, it can be as troublesome as fuel vapour.

Air released from the fuel is oxygen-rich and this must be taken into consideration in rendering the air space above the fuel inert by nitrogen injection or other means.

1.4. Fuel freezing

It will be seen by reference to Fig. 1 that the current specification allows the initial

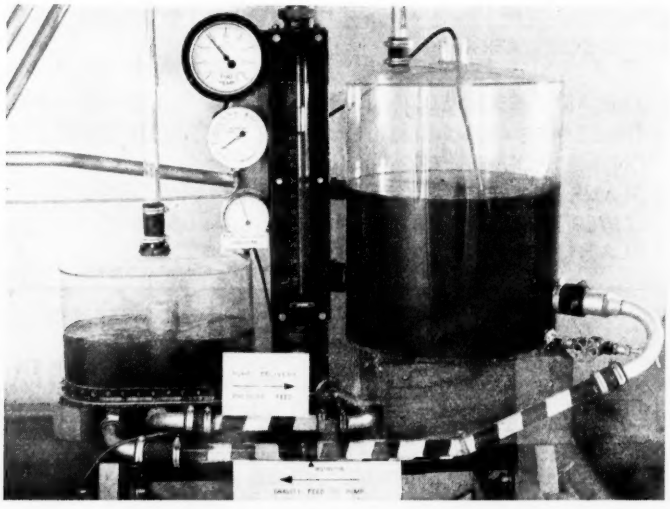

Fig. 5. Altitude chamber rig running at ground level.

freeze point of kerosine to be not higher than −40°C. and Wide-Cut gasoline −60°C. While −60°C. is outside the range of any likely fuel temperature in flight, −40° is too high to meet exceptional conditions. The initial freeze point of kerosine should be lowered at least 5°C to −45°C. It is understood that such a reduction would not seriously reduce the availability of kerosine or increase production difficulties and costs.

Kerosine samples tested in Great Britain by the Thornton Laboratories, Rolls-Royce and de Havilland's have shown consistency in that this fuel could be freely pumped at −40°C, but causes filter blockage at −45°C.

1.5. Water in Fuel

Water in aircraft fuel tanks has always been a serious danger and the advent of high-flying aircraft has placed even more emphasis on the need to ensure that water is not present which would freeze and obstruct the fuel feed and the free working of valves, and other parts, in the fuel system.

Unless precautions are taken to prevent it, water can enter the fuel tanks in any of the following ways:—

(*a*) Free water pumped in with the fuel.

(*b*) Water in suspension carried by dirt in the fuel.

(*c*) Condensation in the fuel tanks.

(*d*) Water in solution in the fuel.

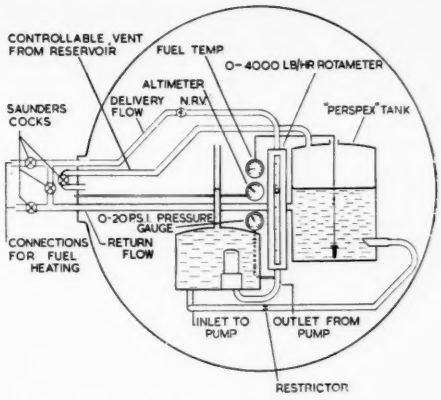

Fig. 4. Altitude chamber test rig.

The seriousness of each of these possibilities prompted a considerable amount of rig and laboratory testing, to which may be added the experience of about 2,000 hours of flight with the Comet, the greater part of which has been made at 35,000 ft.-40,000 ft. with fuel temperatures down to −35°C. Many long distance flights have also been made to Africa and the Far East, using the local fuel available which has varied in characteristics from that obtained in Great Britain.

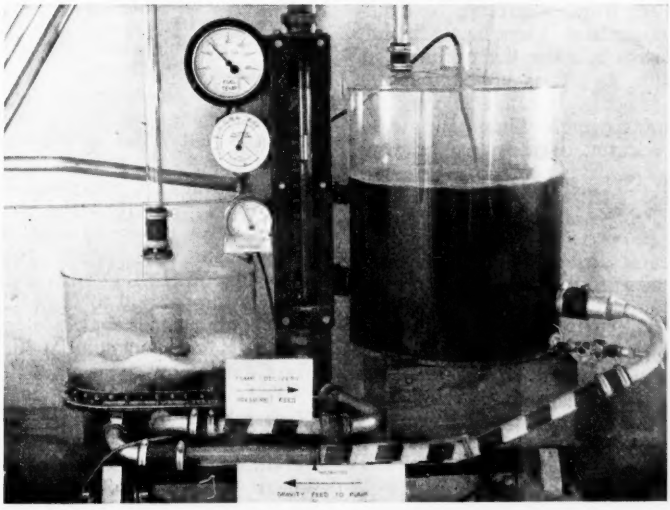

Fig. 6. Altitude chamber rig running just below free boiling altitude.

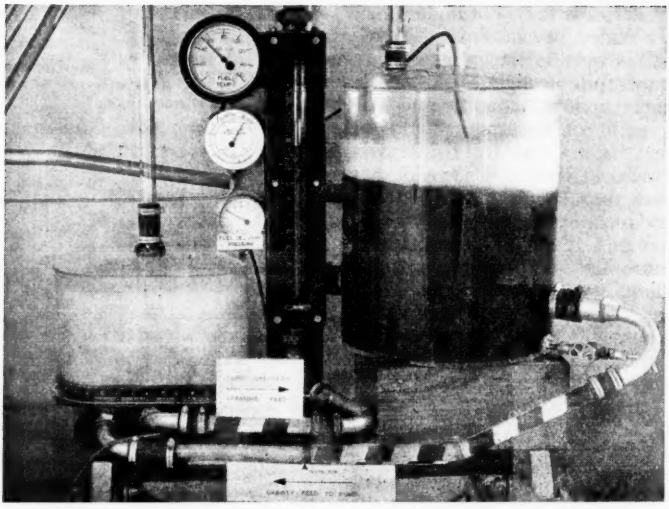

Fig. 7. Altitude chamber rig running just above free boiling altitude.

(*a*) *Free Water*

Flight and rig tests show consistently that free water (*i.e.* water which may have entered into the tanker or container used for fuelling) if pumped into the aircraft will invariably lead to filter blockage by ice. This cannot be over-emphasised, and for civil aircraft there is no reason why fuelling equipment should not have adequate water separation and drainable sumps. Service aircraft operating from an advance base may require primitive and emergency fuelling arrangements which make the exclusion of water very difficult. It is hoped that due consideration is being given to this point and that easily transportable filters and water separators of adequate capacity will be made available.

(*b*) *Water in Suspension*

Water may be carried into the fuel tank on small particles of dirt and since both water and dirt will give trouble, adequate filtration of the fuel into the aircraft is again the answer. A point worth mentioning is that Micronic filters on fuelling units readily become blocked if they are doing their job, and cheap, easily replaceable filter packs are necessary for the maintenance of high-speed fuelling.

(*c*) *Condensation*

Condensation of water in the Comet tanks has not given the trouble anticipated and while, rightly, full attention was paid to water drainage points, no serious quantity of water has been found after several consecutive flights of long duration.

(*d*) *Water in Solution*

After fuelling precautions have been adequately observed, water in solution in the fuel would appear to present the greatest danger of filter blockage.

Figure 9 gives the solubility of water in kerosine and gasoline, and it is worth noting how the possible water content increases with temperature. There may be a slight difference in the water solubility of the two fuels, kerosine and Wide-Cut gasoline, but a single curve is sufficient for practical purposes. As the temperature of the fuel is lowered, water is precipated from the fuel. As the temperature drops below 0°C. this water freezes into ice particles of microscopic size which, with slight agitation, remain suspended in the fuel. 1,000 gallons of fuel, water-saturated at 40°C. will yield, when cooled, about one pint of water. This would approximate to a maximum duration flight of the Comets now flying.

Tests have been made by the Thornton Research Centre and by Rolls-Royce Ltd., during which filter blockage by ice was produced, but tests made by de Havilland's under closely simulated flight conditions produced no evidence of blockage. It may be that slight differences in method of test,

producing ice particles of different size, were responsible for these conflicting results. It remains, however, that critical investigation throughout the flying of the Comets has shown that water in solution and condensation have not resulted in filter blockage or water in serious quantities being found in the aircraft system or filter bowl, and it must be assumed that the small ice particles pass through the filter.

On the other hand, one case has occurred where the filters on one side only of the aircraft blocked and about $\frac{1}{4}$ pint of water was taken from one filter bowl. This quantity is more than the amount which could have come out of solution in this case, and since still more water was found in the tanks, the only conclusion which can be drawn is that free water had been inadvertently introduced into the tanks.

Various methods of overcoming filter icing are possible:—

(*a*) Providing a filter by-pass.

(*b*) Injecting anti-freeze, such as Methanol, upstream of the filter.

(*c*) Heating the filter element.

If measures to prevent water entering the aircraft tank are considered unreliable, it is certain that means must be provided to ensure the fuel feed when the filter clogs. The risk of such a possibility will depend upon the type of aircraft, the operating conditions and aerodrome facilities, and these factors may need to be taken into consideration when deciding on the degree of anti-icing to be provided.

The best method of combating this problem would be to provide in the fuel tanks a container of solid anti-freeze, so arranged that it can be easily withdrawn for renewal. Unfortunately, a suitable solid anti-freeze that will be practically insoluble in the fuel, yet soluble in water and not attack the rubber tank sealing, or have other detrimental effects, has yet to be discovered.

Chromium Trioxide was suggested by the Thornton Research Centre, and this looked very promising in fulfilling the first two conditions, but it was found that rubber sealing disappeared in about 48 hours.

1.6. Effect of Fuels on Fuel System Components

In the table (Fig. 1) is given the maximum percentage Aromatic Hydrocarbon content of the two turbine fuels being considered.

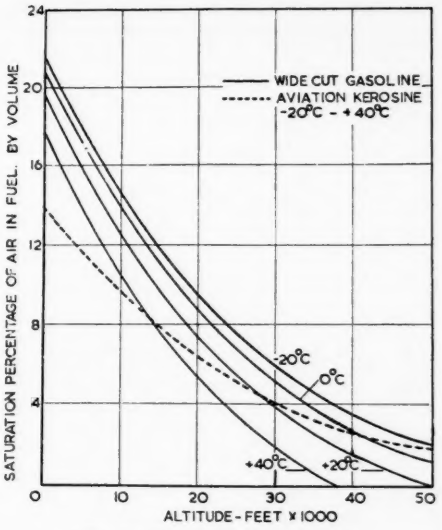

Fig. 8. Solubility of air in fuels.

Aromatic hydrocarbons are the constituents of the fuel which cause swelling of synthetic rubbers used in the construction of bag tanks, seals, and so on. After considerable research, synthetic rubber blends have now been produced which successfully resist excessive swelling, while retaining flexibility at low temperature. Freedom from trouble in this connection depends upon very careful control of the rubber mix and upon ensuring that the

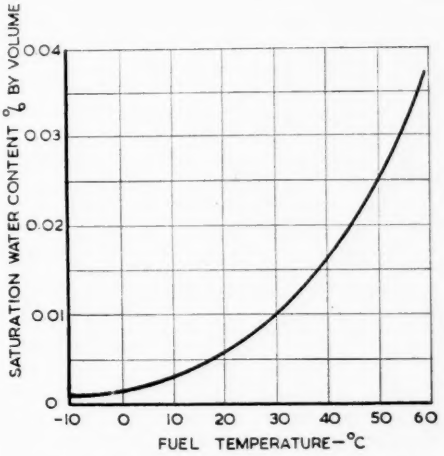

Fig. 9. Solubility of water in kerosine and gasoline.

fuel specifications do not allow the present maximum of 25 per cent. aromatics to creep up. Experience has taught that unexpected corrosive effects on metal parts can result from combinations of fuels and bag tank materials. This must be kept in mind when investigating new materials. Similarly, the temptation to use magnesium for fittings inside fuel tanks, or anywhere in the fuel system where there is a possibility of water settling, must be resisted.

1.7. Permittivity of Fuel

The increasing use of capacitance-type fuel gauges has made it necessary to obtain values of Permittivity of fuels. Large variations in value will make accurate fuel contents reading difficult by this means. Aircraft using fuels ranging from kerosine to Aviation Gasoline will be particularly at a disadvantage.

There would seem to be a good case for including values of Permittivity in the fuel specification and it is probable that the oil companies would now have sufficient information to do this.

As a rough guide, the relative Permittivity varies with specific gravity, regardless of type of fuel, as shown in Fig. 10.

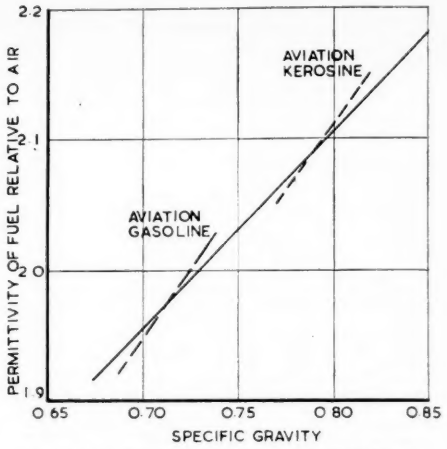

Fig. 10. Permittivity of turbine engine fuels.

1.8. Fire Risk

Throughout fuel system design the possibilities of fire must always be before the designer. Many possibilities of danger can be eliminated, or reduced, but the fact remains that an aircraft carries vast quantities of inflammable fluid. Thirty per cent. to 50 per cent. of the take-off weight of a turbine-engined aircraft is fuel. It is of paramount importance therefore that the relative safety of fuels should be considered, particularly for civil aircraft.

The fire danger potential of kerosine and Wide-Cut gasoline can be assessed from an examination of the following:—

(*a*) Pressure/temperature explosive range.

(*b*) Flash point.

(*c*) Spontaneous ignition temperature.

1.9. Explosive Range

Taking a fuel temperature range of +40°C. to −35°C., which is a likely fuel temperature range on a turbine transport or bomber aircraft, it will be seen from the envelope curves given in Fig. 11, that kerosine will produce an explosive mixture in the tanks at the high temperatures, while Wide-Cut gasoline is dangerous at the low temperatures. However, on the climb and cruise the fuel drops in temperature and moves away from the kerosine explosive range towards the Wide-Cut gasoline range.

The way this happens on the Comet is shown by the shaded area on Fig. 11. There is little doubt that for civil aircraft, in flight, kerosine is the safest fuel, while Wide-Cut gasoline in this respect is worse than Aviation gasoline.

Aircraft with rapid rates of climb and of short flight duration will remain relatively longer in the kerosine danger zone when operating from hot climate aerodromes. Under these conditions there would be little to choose between the two fuels. Kerosine presents its greatest danger at high ambient temperatures before flight, and on the initial take-off and climb. Even so, the danger is from the lean mixture limit and any air draught will tend to produce a safer condition. Wide-Cut gasoline on the other hand, is dangerous from its rich mixture limit and an air draught will weaken the mixture into the explosive range. While Fig. 11 may be true of the conditions inside a tank, it is not a true picture of the danger presented by these respective fuels from vapour issuing from vents or fuel spillage on the ground, where a slight breeze will reduce the fire potential of kerosine and it will be limited to a small area. But the danger from gasoline would spread on the breeze.

1.10. Flash Point and Rate of Flame Propagation

The rates of flame travel for kerosine and Wide-Cut gasoline are about the same, namely 4 ft./sec., at or above the respective flash-point temperatures of the fuels.

The flash-point therefore is the most significant consideration from the aspect of rate of fire travel. It is obvious that flames can only spread over a fuel surface if the latter is hot enough to produce an inflammable vapour-concentration. Thus at temperatures exceeding the sea-level flash-point of kerosine, namely 38°C., both fuels are equally dangerous.

The lower the fuel temperature drops below 38°C., and it is seldom above this figure, the more difficult it becomes to start a kerosine fire, while gasoline of 3 lb./in.^{2} R.V.P. remains highly dangerous down to −23°C. The significance of this is that in the event of a crash, unless this happens immediately after take-off in a hot climate, gasoline is ready to be ignited immediately, while kerosine must be heated up considerably to enable the flame to travel; it is this interval which gives the crew and passengers in a crashed aircraft a chance to escape and also gives the fighting crews a chance to extinguish the fire before it takes control.

This considerable safety advantage now offered to civil aircraft should not be lost by the use of higher volatility fuels. Kerosine fuel may add more to safety than the heavy and costly fire preventive measures now being built into aircraft, and while it is not suggested that these measures are unnecessary, the combination of modern fire precautions with kerosine fuel can result in a new standard of safety for future civil aircraft.

Military aircraft are subject to other considerations of comparative risk and supply problems.

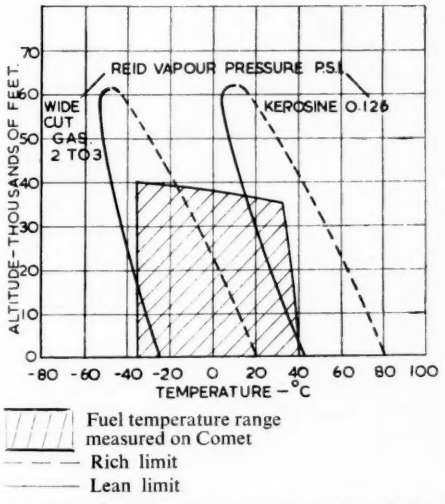

Fig. 11. Explosive limits as affected by altitude and fuel temperature.

1.11. Spontaneous Ignition Temperature

The value of the Spontaneous Ignition Temperature (S.I.T.) of a fuel depends much upon the method of test. Fig. 1 shows that by the open steel plate method, giving an S.I.T. of about 650°C., there is little difference between the two fuels, and this might be expected to apply also to the steel tube method of test, giving for kerosine an S.I.T. of 200-238°C. The wide difference in S.I.T. between the two methods has some considerable significance, since the open plate method could represent the conditions of a jet pipe, or jet pipe lagging freely ventilated. Practical tests of playing a kerosine spray on to a jet pipe, running at full power, failed to produce ignition, which would tend to confirm this.

The steel tube method of test, on the other hand, would be comparable to fuel in a vent pipe coming in contact with a surface at 200°C., such as may, in certain circumstances, result from using engine compressor air for tank pressurisation.

2. Some Aspects of Detail Design

2.1. Fuel Pumps

It is generally realised now, that fuel pumps fulfil two functions. Firstly, to supply fuel to the engine pump at sufficient pressure to prevent any vapour release in the feed system or engine pump where cavitation can occur. Secondly, to provide the necessary agitation in a fuel tank to cause air to come out of solution in the fuel and escape from the tank vents before it can enter the feed pipe system.

Figure 6 shows air and vapour coming off the impeller and being led clear of the ingoing fuel by the vapour guide cone on the pump.

It is obvious from this consideration that pumps should not be installed in feed lines

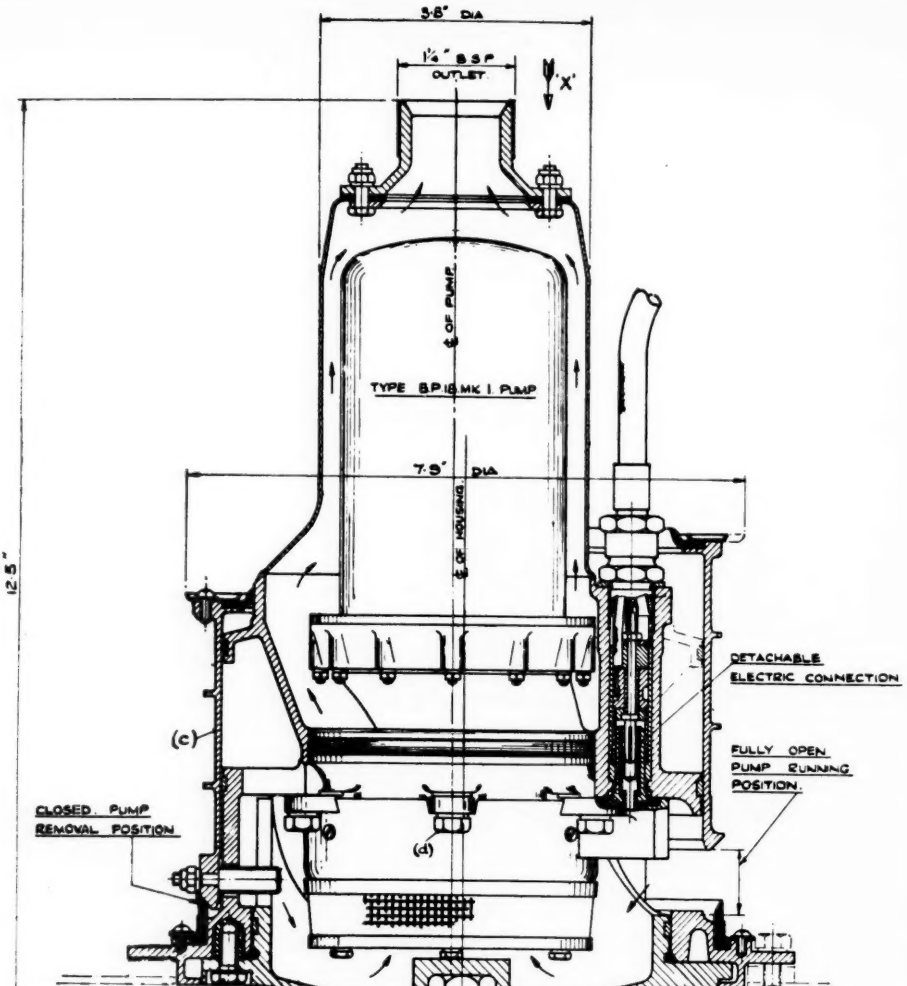

Fig. 12. To remove booster pump from aircraft, leaving fuel in tank: Switch off pump. Remove screws (a) and rotate bottom plate (b) to disengage bayonet fixing, and close outer sleeve (c). Remove bottom plate (b) and unscrew pump fixing screws (d). Pump can then be withdrawn.

where there is no means of escape for this air and vapour.

If, however, pumps are installed in tanks with provision for air and vapour clearance, they provide an answer to many of the acute problems experienced in the past.

The particular characteristics of the pumps now generally used, whereby the delivery pressure falls to negligible proportions when the pump becomes uncovered, can be used to good advantage to reduce the unusable fuel in a tank to a minimum. By arranging in the Comet system for fully submerged pumps to be switched on in one tank, when the previously used tank is nearing the empty stage, the pumps can be left running to pick up the

last swilling gallon without fear of forcing air into the feed system.

There are ten S.P.E. pumps in the present Comet system, that is two pumps in each tank so that full duplication is provided. It may be said, however, that no pump failures have occurred. This good record is no doubt due to the ready co-operation of the makers in making extensive tests under conditions simulating flight cycles. As with all items of this nature, the value of prolonged testing under the right conditions cannot be over-emphasised.

In this case a small Kelvinator cold chamber was converted into a test rig and it was arranged by means of an altitude chamber inside it, to simulate flight cycles of temperature, pressure and pump delivery rate. In all 1,500 hours of running was done in this way and as a result several improvements were incorporated.

A diagram of the B.P.18 pump as used in the Comet is shown in Fig. 12. The pump can be removed without draining the fuel tank by removing a cover plate on the underside, which automatically draws a sleeve down over the pump housing. The pump can then be withdrawn for inspection or replacement.

2.2. Tank contents gauging

The need to have, at all times during flight, an accurate knowledge of the fuel available in an aircraft and the rate at which it is being used, has always been important but the much higher fuel consumption of turbo-jet engines, with the consequent necessity to carry more fuel, has accentuated to an important degree the need for a new conception of accuracy. The critically high fuel weight to all-up weight of the turbo-jet transport, with the proportionally high fuel reserves carried at the expense of useful load, does not permit lavish margins to cover errors of gauging.

While fuel tanks were of relatively small size and simple form, the float-operated gauge served its purpose, but it can no longer be fitted effectively in large shallow tanks with many baffles, such as are now incorporated into wing structures, or the tanks of complicated form necessary for the smaller high performance aircraft. A gauge of improved flexibility in fitting and of greater accuracy was required.

By the initiative and ingenuity of those who pioneered the capacitance-type gauge it looked as if this difficult problem was solved and indeed it has been partially. Experience with the Comet, however, has shown up many factors which were not originally known or appreciated and much concentrated effort must continue in order to devise means of compensating the effects of unit variations, differences in fuels and wide temperature changes.

The capacitance gauge is useful in its present state, but it will only *begin* to fulfil its true function when the maximum overall tolerance of accuracy under flight conditions is within ± 2 per cent.

Other possible methods of tank gauging should be investigated energetically but the only final proof of their worth will be tests on an aircraft under the most arduous conditions.

2.3. Fuel system fittings

The need to keep the pressure losses low through pipes and fittings is now well appreciated and much has been done to provide unions, fuel cocks, and so on, with the full nominal bore. It is important that this be stressed in the design of all such parts, in view of the extremely high fuel flows demanded by turbine engines. It is not unknown for pipe sizes to have to be increased above that required, in order to use unions or fittings of sufficient bore.

These remarks apply to some flexible pipes which, because of their fire-resistant construction, have very thick walls which make full bore end fittings difficult to achieve.

2.3.1. *Flexible Hoses*

In many cases attempts to use flexible pipes with the standard end connections has been frustrated by their lack of flexibility and it becomes a necessity to make special end fittings to suit the only angle of take-away possible. There is great scope for the design of a light weight, really flexible, fire-resistant hose and it is hoped that work is proceeding in this direction. Low pressure non-fire-resistant hoses now fulfil their function well and it is gratifying to see the low resistance end fittings which are being produced with them.

2.4. Joint seals

The difficulty of making joints leak-proof against kerosine is well known. Kerosine has the habit of oozing out and spreading to the

greatest disadvantage. In the author's experience, considerable efforts were made to find a flat face seal which would resist kerosine, remain tight down to $-40°C.$, and not squeeze out under the pressure of the joint when warm. The remedy however was to have a metal plate insert in the flat seal or to use "O" ring seals which will fit into a rectangular groove of just about the same cross-sectional area as the rubber ring.

Alternatively, the "O" ring can fit into a spigot and be pressed into a chamfor. The principle of trapping the rubber into a space in which it will just fit so as to prevent the rubber flowing, is the main requirement and has proved quite successful in every application.

2.5. Pipes

Pipe runs always tax the ingenuity of the designer in satisfying the requirements of avoiding inverted traps in fuel feed lines, "U" bends in vent lines and allowing for expansion and ease of fitting.

Anything that can be done to keep pipe sizes down is obviously of great advantage in reducing weight and achieving a satisfactory run of pipe.

When designing, however, it is always wise to bear in mind that engines will be up-rated, or engines of greater power fitted, and to design initially to the smallest possible size may lead to the necessity for considerable future alteration.

3. Fuel System Design

3.1. Fuel tanks

The necessity to find space in an aircraft for greater quantities of fuel and the continual quest for weight reduction has led to the present-day practice of using the aircraft structure to contain the fuel, either directly, by making spaces in the structure sealed compartments, or by lining these spaces with a thin walled flexible bag. The former method is now referred to as Integral Tank Construction and the latter, Bag Liner Construction. The self-contained rigid tank has been relegated to the outside of the aircraft in the form of wing-tip or pylon tanks.

There would be no point in arguing the superiority of Integral or Bag Tanks, except that the former allows the greatest possible fuel capacity within a wing.

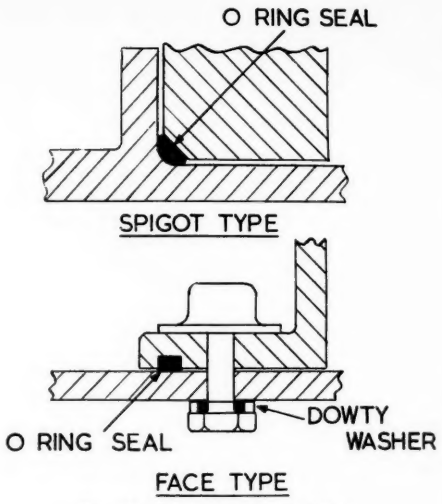

Fig. 13. Ring type sealing joints.

There are advantages and disadvantages with each method and the choice will depend upon the application.

3.1.1. *Integral Tanks*

Much disappointment has been experienced in the past with these tanks, but if the right approach is made to the design, they can be successful and possibly give less trouble than any other form of tank. The vital factor for success is to give the utmost consideration to the tank design in the early stages of the structural layout. It will most certainly mean that the important basic structure is dictated by the tank, and the sealing problem in minute detail must be given full consideration from the beginning of design. Some factors which might be considered with this approach, for example, would be, the use of Redux and bolts and the complete avoidance of rivets in the tank regions; clean boundary corners inside the tank, free from angles or stringers, and the careful design of sealing joints for tank fittings and covers.

It is easier to make integral tanks in a structure bounded by thick skins as now used in high-speed aircraft, because of the necessity to countersink bolts on the external surfaces and to provide flat facings for fittings and cover plates.

As a general principle the designer must aim to achieve sealing without the aid of

plastic sealant, using this sealant finally as a second line of defence only. The advantages of the integral tank are mainly functional; relatively wide ranges of pressure differences can be taken, internal and external fittings such as feeds, vents, tank gauges, and so on, are easily accommodated and the problems associated with the handling and fitting of bag liners are avoided.

An essential part of the development of an integral tank is thorough Rig testing of a specimen tank incorporating the proposed structure sealing features.

Figure 14 shows the test tank made for the Comet rigged up for repeated torsional test. The tank joints were white-washed and dyed fuel used so that leaks could be easily traced. Many test runs were made, the final test being a five-hour run in a cold chamber with the fuel temperature at $-40°C$. and torque equivalent to $\frac{1}{3}$ the failing load applied at the rate of 20 cycles per minute.

3.1.2. *Bag tanks*

While bag tanks may be fitted, of necessity, where difficult structural problems and light structure prohibit the design of integral tanks, they have further advantages in being unaffected by normal structural deflections and are possibly more resistant to failure in the case of crash. Great care is necessary in storage, handling and fitting the bags; in fact most leakage trouble may be traced to lack of care in these respects.

Venting must be arranged to give at all times a greater pressure inside the bag than in the tank compartment, to avoid the bag sucking in and putting heavy local strain on the attachments and forcing fuel out of the vent pipes. Careful attention must also be given therefore to the tank compartment pressures in flight.

The compartment in which the bag fits must give the bag complete support and have a smooth interior free of all cutting edges. Due to the difficulties of tracing a leak from outside, because of the spread of fuel around the surrounding structure, easy access to the interior of the bag, or easy removal, is necessary. No mention has been made of self-sealing bags since they are fitted for the sole purpose of added safety in combat aircraft, but apart from being more robust they conform with the general comments given. The material of the bag will depend much upon its duty, but resistance to low temperature is probably the most difficult consideration to meet and consistancy in the material properties is essential. Careful design in the light of experience gained is the best guarantee of success. To quote a case of what not to do; serious failures occurred around the filler of a bag tank and it was found that, the filler being attached to the wing skin caused local cooling of the bag where it was supported at the top by the filler. The consequent local hardening of the bag material, together with the pull of the bag,

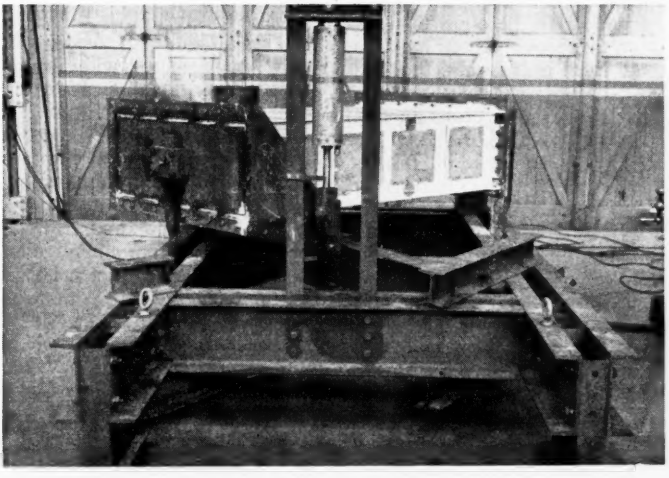

Fig. 14. Repeated torsion test on specimen integral tank.

caused splitting. The thickness of the bag material will depend upon the duty it has to perform and the degree of handling control which can be expected.

The Comet centre tank uses 0.020 in. thick material reinforced with nylon outside and this has given reasonable satisfaction.

The method of attaching the walls of the bag to the container has presented some difficulty in the past and rubber moulded studs pressed through circular holes in the plate support have not been particularly satisfactory. Lacing the top of the bag to the structure is good if it can be done, since it gives ample support to prevent droop. Tying the vertical corners also keeps the bag well in place, but a good positive fixing stud which can be attached to the structure from inside the bag would provide the most convenient and universal method of attachment.

The method of sealing the bag where, for example, access holes occur, must be considered carefully.

The bag material between the clamping faces must be prevented from flowing out of the joint and exposing the bolt holes. Careful attention to detail points like these is vitally necessary for success.

3.2. Fuel feed

In laying out a fuel system for turbine-engined aircraft, the principal point to bear in mind is that, unlike piston engines which can usually deal with a certain amount of air or vapour being delivered with the fuel, the turbine engine is much more particular in this respect. It is a good rule therefore to work on the assumption that air or vapour must be entirely prevented from passing into the feed lines.

A suction feed can be dangerous in this respect, particularly at low fuel levels; on the other hand, as already stated, tank pumps can be made to meet the requirement of feeding at low fuel levels satisfactorily. It is of advantage to arrange baffles and non-return valves in the tank to form a compartment around the tank outlet in such a way as to trap fuel as it swills and thus ensure as great a head as possible.

Air or vapour in the feed line can be due to low pressure and/or high line velocity and local restrictions, the effect of which was shown in Fig. 6. Again, tank booster pumps will provide the answer, together with a simple analysis of the pressure losses in the feed system and adjustment of pipe sizes to ensure that under all conditions a full bore liquid flow is maintained above the minimum pressure.

With something like a 6 to 1 ratio between the engine consumption at sea level and cruising conditions at altitude, it may be thought that the sea level case would cover all other conditions. If weight and space were not serious considerations this would be the case, but advantage can sometimes be taken of the compensating effect of high atmospheric pressure at sea level, with low booster pump pressure due to high flow, and vice versa at altitude. Or in other words, to investigate the engine pump inlet requirements on an absolute pressure basis, bearing in mind that the restrictive effects of the engine pump internal passages must be taken into consideration.

Negative "g" conditions present the most difficult circumstances under which air must be prevented from entering the feed lines. Fighter aircraft, and indeed all aircraft likely to be thrown into abnormal attitudes, require special provision to maintain a continuous fuel feed and means for doing this are now well known. Whether special negative "g" provision is required on civil transport aircraft depends upon the operating conditions for the particular aircraft, and upon the engine and engine fuel system. The Comets, throughout their flying, have shown no need for such provision and on ground test the engines regained normal running after the feed pipe had been opened to full air bleed for 8 seconds. Conditions in the air, however, may reduce this time.

The difficulty of feeding fuel from thin swept-back wings without disproportionate weight and complication, needs careful consideration in the future. In addition to the necessity of providing at least two feeds from each tank to deal with nose-up to nose-down attitudes, complicated baffling is required to control the travel of fuel in the tanks. Venting and pressure fuel then become correspondingly complicated and high loads due to fuel head can be imposed on the tank walls. It is not easy, however, to see how to avoid using the wing space for fuel when large capacity tankage is required and it may be that a new method of feed, such as "squeezing" the fuel from the tank, may be possible.

The approach to the design of the fuel system for transport aircraft must differ from that for fighter aircraft. The former should

be as flexible as possible in the way fuel can be used and in the interest of simplicity of units which the crew can normally be expected to operate to a procedure.

Fighter aircraft, however, must be fully automatic in all respects. Unfortunately this leads to a growth of complication on an aircraft of a size least able to take it, and which is maintained by personnel of limited experience under difficult conditions. The designer may well ask whether the steadily growing requirements are not defeating the object of producing a useful fighting unit.

3.3. Vents

Vents should be simple stack pipes projecting out of the tops of fuel tanks, but in fact they present some of the most difficult problems of a fuel system. The conditions under which the vent must operate may be stated briefly as follows:—

(*a*) The vents must be adequate in size to allow pressure in the fuel tanks to be kept within the required limits.

(*b*) All flight attitudes and positive and negative aircraft accelerations must be considered from the point of vent spill.

(*c*) Traps must be avoided which may accumulate fuel or water.

(*d*) The vent outlet must not ice up or be in a region of the aircraft where high or low surface pressure is detrimental.

(*e*) Vapour or fuel which may discharge from the vent must not do so in a region where it can be a fire hazard.

(*f*) The designer must be on his guard against making the vent a natural syphon.

It is possible to meet all these conditions, at least theoretically, by using special float valves, gravity valves, and so on, but if they fail to function the result may be serious. The aim therefore should be to achieve all the requirements with a simple pipe run, resorting to the more complicated device when there is no alternative. If the arrangement of the fuel system is such that a central tank can be used as a master, then many difficulties can be overcome by running the other tank vents into it and venting the master tank separately. Thus the master tank catches the vent drainage from the other tanks. Care must be taken, however, that the master tank is of sufficient depth and size to provide adequate air space. If all vent outlets could be flush with the outside surface of the aircraft there would be little trouble from ice. Unfortunately, the low pressures at such surfaces cannot always be tolerated, particularly if the tank is of the bag type. The best remedy is probably to have a flush vent outlet and, with a suitable relief valve, supply a small positive pressure in the tank from an ice-protected ram intake, or engine compressor source.

Swept-back wing tank systems are apt to become extremely complicated since there is no consistantly high place in the tank from which the vent outlet can be taken. It becomes necessary, therefore, to vent the fore-and-aft and possibly the inboard and outboard extremities. Valves then become necessary to check the fuel when the vent opening is submerged. Fore-and-aft accelerations and the consequent risk of vent spill can be prevented by running the vent pipe the full fore-and-aft distance of the tank so that the inertia of the column of fuel in the vent pipe balances the temporary acceleration head of the fuel in the tank.

An arrangement of vents which will syphon can usually be recognised on the drawing board if it gets as far as that, but syphoning with bag tanks can be much more elusive.

A typical case where, once fuel has entered the vent pipe it will practically empty the tank, is provided by the depression due to the head of fuel in the vent pipe causing the flexible side of the bag to squeeze in and keep the vent outlet submerged. The only remedy in such cases is to relieve the depression in the bag by a separate inward venting source.

3.4. Tank Supercharge

Reference to Fig. 3 shows that while kerosine requires no tank supercharge to prevent boiling, Wide-Cut gasoline requires up to $2\frac{1}{2}$ lb./in.^{2} to meet the conditions of reduced pressure at 50,000 ft. altitude and 45°C. fuel temperature.

Civil aircraft can well do without the additional complication of a pressurised vent system unless it is justified as a means of emergency fuel feed, or to increase fuel jettison rate.

Military aircraft with high rates of descent demand high rates of inward venting to the tanks which, with a non-supercharged vent system would necessitate vents of a size which would be extremely difficult to accommodate through ribs and spars without producing water traps and restrictions.

Supercharge by air or inert gas is necessary in such cases if depression cannot be permitted. The wing design, however, must take the tank supercharge pressure into consideration from the strength aspect, since this pressure is additive to the normal wing surface suctions which are usually a maximum under low level conditions of high-speed flight.

If reliance is placed upon pressure to prevent tank collapse, due consideration must be given to the vulnerability of the source of the pressure and it may well be that a ram air supply is the least likely to be affected by engine failure or combat damage.

3.5. Fuel Tank Explosion Prevention

While the author has little experience of the relative effectiveness of the various means of preventing tank explosion, remarks prompted by the somewhat discouraging efforts to find reasonable accommodation for these systems on an aeroplane may be of some use. Firstly, the need for such protection on military aircraft is quite clear after witnessing an incendiary bullet enter a tank containing an explosive mixture. There is no case yet, however, to justify the fitting of tank protection on civil aircraft, particularly if kerosine is the fuel. The generally known methods of tank explosion prevention are:—

(*a*) Rendering the space above the fuel inert by:—

(*i*) Displacing the air with nitrogen.

(*ii*) Displacing the air with exhaust gas.

(*b*) Suppressing the explosion.

Nitrogen has been the only method developed in Great Britain and it has proved a very poor answer on anything but the bigger aircraft because of the large quantities required to meet the conditions of

(*a*) Taking the place of the fuel used.

(*b*) Purging oxygen-rich air released from the fuel.

(*c*) Providing the large quantities required for inward venting in the dive which is then wasted overboard on a subsequent climb.

With the difficulties of metering the gas at widely varying rates of flow from high pressure bottles and the resulting weight and complication involved, the system has now reached the stage when it is unsuitable for fighter-type aircraft.

Exhaust gas systems have been used in America and these are alleged to weigh very little. There are difficulties, however, in tapping completely inert exhaust from turbine engines, due to the large amount of unburnt air present. No doubt this problem is being investigated in this country. Explosion suppression, that is, using the initial pressure rise in the tank to operate a suppressive medium, was originally developed at the Royal Aircraft Establishment and offers a brilliantly conceived solution to this difficult problem. There seems to be no doubt about the effectiveness of this method and since it operates only when required it would appear economical in maintenance time and material.

This system however needs developing in detail before it can be installed effectively and much work remains to be done. In the meantime the aircraft designer is apprehensive as to what the future holds in this respect.

3.6. Fuelling and Off-loading Fuel

Fuelling large aircraft through filler points in the top of the tanks is a long and tedious operation with considerable hazards to operators and aircraft due to fuel spillage and slippery wing surfaces, step ladders, and so on; under-wing pressure fuelling offers the best way of overcoming all these difficulties, while cutting down fuelling times to the minimum. The greater quantities of fuel necessary for turbine-engined aircraft have given added impetus to the design of pressure fuelling systems. Rapid off-loading has become necessary also to save time, particularly where last minute loading changes have to be made. The need for pressure fuelling, however, should not be taken for granted.

The role of the aircraft must be considered carefully to avoid piling up "Weight, Complication and Cost" without some worthwhile return. The weight of the Pressure Fuelling System alone, on a fighter of 1,000-gallon fuel capacity contained in six tanks, worked out at 78 lb. Pressure fuelling has been used in the Comet from the day it first flew and there is no doubt about the necessity for it on this type of aircraft. It might be of value therefore to give some of the underlying principles which controlled the design of the system.

Two fuelling points are provided and from these all tanks can be filled simultaneously, in addition each tank can be selected for

fuelling independently. Control is provided from a panel in each wheel-well which is fitted with contents gauges and selector switches. Fuelling at 200 Imperial gallons per minute per refuelling point was the aim and this has been achieved.

Valves developed by Flight Refuelling Ltd. are used to control the feed into each tank and these are placed as low in the tank as possible for two reasons. Firstly, so that the ingoing fuel does not agitate the surface of the fuel when the tank is approaching full; and secondly, so that the same valves could be used as a means of drawing fuel out of the tanks. The full level is controlled by cut-off switches which react electrically back to the tank valves. It was necessary to ensure that negligence in filling, or failure of any part of the fuelling system, would not result in overfilling the tank and possibly bursting the wing. The Comet, therefore, has two automatic cut-off levels; the first operates when the tanks are nearly full and the tanks are filled up to this level at maximum input. They are then topped up at a reduced fuelling rate to a level controlled by the second cut-off switch. The fuelling operator can override the automatic fuelling at any time and is given warning that the cut-off levels have been reached. However, if he does jam a piece of wood in the control switch and go off for a cup of tea with the fuelling truck going full bore, and if the cut-off switch should choose at this time to go unserviceable, each tank is fitted with a " blow-off valve " which supplements the vent overflow and prevents the pressure in the tank from rising above the safe valve.

It may be said here that the greatest difficulty with automatic cut-off systems is to find a way to position the cut-off switch high enough in the tank. As with vents and fuel feeds, this becomes increasingly difficult with shallow flat tanks and swept-back wings. A pressure-operated cut-off may be better for this reason than the float-operated cut-off, but it would be more difficult to control the air space at varying filling rates. Fig. 15 shows the Comet inboard wing tank and illustrates many of the points discussed in this Section. The outboard wing continues on from rib. 7 shown.

4. FUEL SYSTEM TESTING

4.1. RIG TESTS

Although in many respects there is no substitute for flight testing, it cannot be denied that it is a costly, lengthy and somewhat late

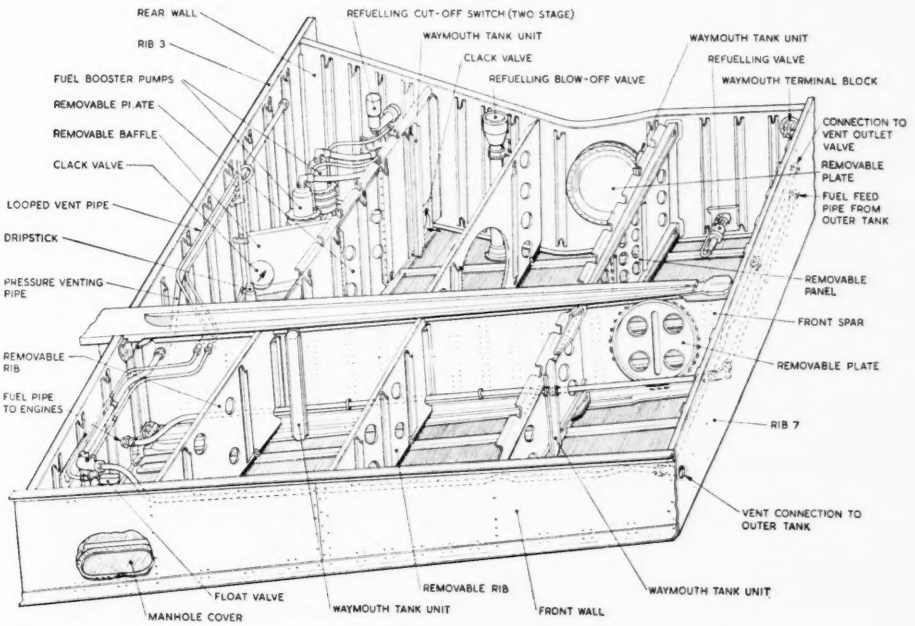

Fig. 15. Comet inboard wing tank.

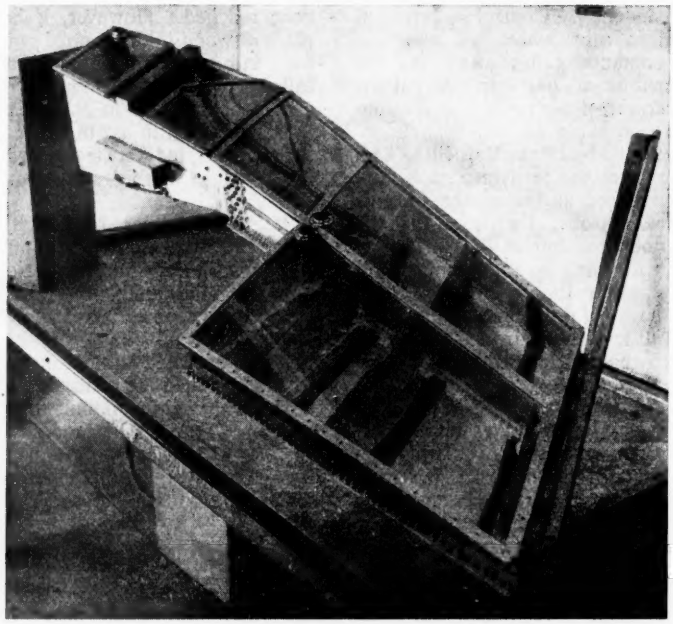

Fig. 16. Wing tank model.

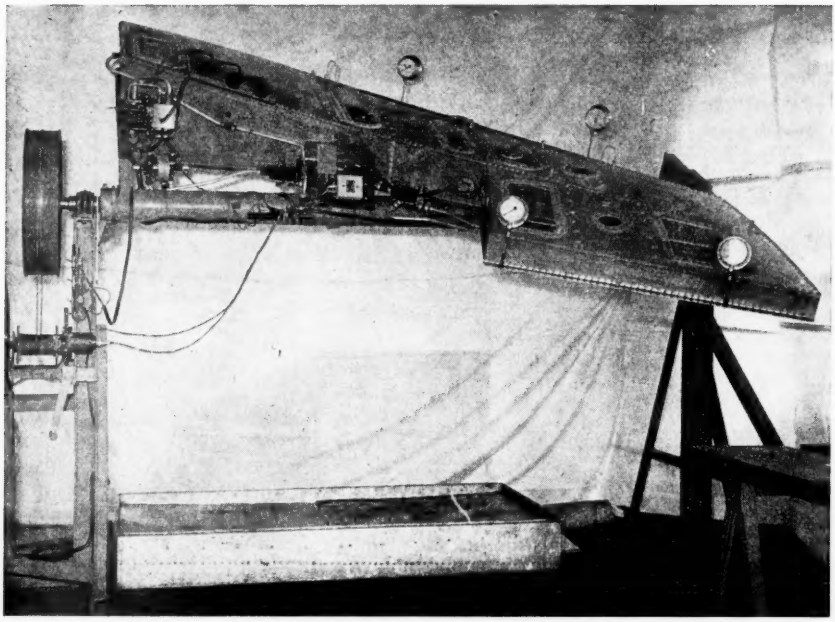

Fig. 17. Rotating fuel system rig.

method of proving a fuel system. Therefore, it will pay to do as much rig testing as possible. How elaborate the rigs should be, will depend on the extent of the problems involved, but experience has shown that it is the unsuspected troubles which are likely to prove the most difficult. For this reason any rig should represent as closely as possible the system to be tested.

Outlay in rigs and equipment will be amply repaid in time saved on the prototype, since rapid development is an essential factor in putting an aircraft into production. Flight testing on modern aircraft can easily reach the stage when the unserviceability of test instruments alone will cause the loss of much flying time. When dealing with a complicated system the following procedure has been found successful in keeping pace with design progress. It applies particularly to difficult wing installations of the swept-back type.

A small $\frac{1}{4}$ scale model is first made of the wing, with the tank compartments accurately positioned. The top surface is made of Perspex so that the behaviour of the fuel inside can be observed. The wing model is mounted on pivots to allow rotation in the pitching plane. Fig. 16 shows such a model.

From this simple model, the run of the fuel may be determined at all angles and suitable check baffling devised. The best arrangement of vents can be seen, and drains, feeds and tank gauge units can be positioned to the greatest advantage. The model is also of value to the design office for reference in connection with tank wall load calculations, c.g. travel and general design problems. While the small-scale model is being used for this purpose a full-scale fuel system rig may be under construction. This will incorporate the designed feed, vent, filling and drainage systems and, if possible, the tank gauges. This full-scale rig should be made to rotate in the pitching and rolling planes. For fully aerobatic aircraft 360° pitching and 180° rolling either way is desirable. For transport aircraft it is sufficient to cover maximum nose-up and nose-down pitching and about 10° rolling either way. Complete functioning tests can then be made and detail units designed for the aircraft, fitted for check as they become available.

When space limitations, or the size of the aircraft, prohibit making a full-size rig, it has been possible to obtain the necessary data by making this rotating rig half size (such a rig is shown in Fig. 17) and supplementing it with a full-size static rig for flow check A half

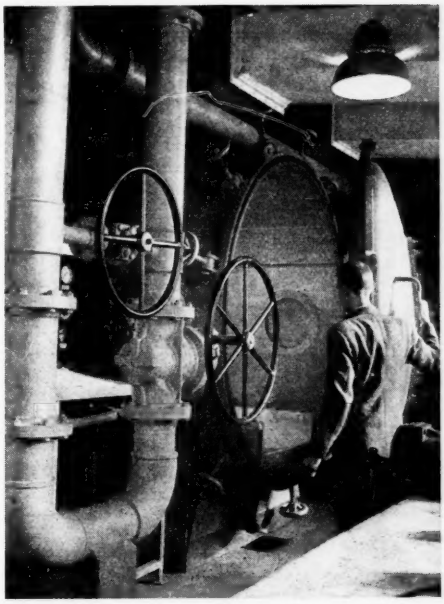

Fig. 18. Fuel system altitude chamber.

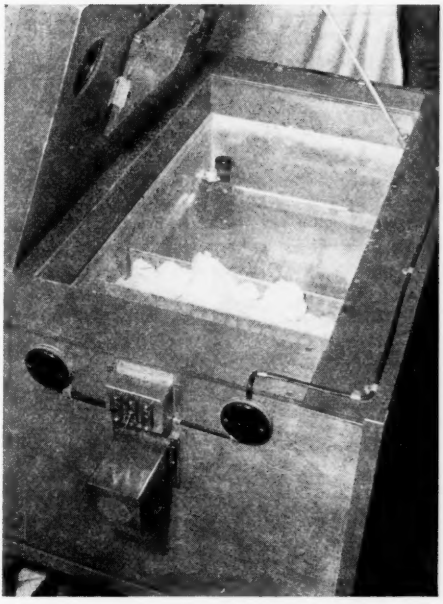

Fig. 19. Small cold box.

Arrangement of skin thermocouples in port wing

Arrangement of fuel temperature bulbs in port and starboard outboard fuel tanks

Fig. 20. Measurement of wing and fuel temperatures in flight: D.H.106 Comet.

scale rig, however, presents some difficulty in the scaling down of vent and feed sizes, since volumes and flows will be $\frac{1}{8}$th full-scale, pipe bores will be $\frac{1}{4}$ scale, and gravity heads $\frac{1}{2}$ scale.

A fuel system test house has been part of the testing facilities of the de Havilland Aircraft Company for several years now and it has been kept continually in full employment.

This test house is provided with forced draught to take away fumes and vapours, an adequate anti-fire sprinkler system, flame-proof doors and rapidly operated dump valves so that in emergency fuel can be run out of the house into underground containers.

All electrical fittings and equipment are flame-proof. Thus, with due precautions taken by the staff, work can proceed rapidly without the restrictions imposed by working outside or in buildings not equipped with the necessary safety features.

The working equipment consists of:—

(*a*) A relatively small altitude chamber (Fig. 18) to which it is hoped to add refrigeration.

(*b*) Fuel containers which can be balanced to the altitude chambers.

(*c*) A steam fuel heater.

(*d*) Pumping equipment for lifting the fuel from underground tanks.

(*e*) A small cold box—cooled by means of broken Dry-cold (Fig. 19).

(*f*) Drainable metal work-benches and drip trays.

(*g*) Flame-proof, variable speed 10 h.p. electric motor.

The remaining important requirement is space, since rigs simulating aircraft systems cannot be unduly cramped.

The equipment described will enable most fuel system problems to be investigated, from fuel feed and venting systems to details such as seals and pipe joints. In addition, the facilities are available for producing quickly a particular phenomenon such as boiling or frozen fuel, so that persons concerned can see for themselves and have a better understanding of the medium with which they are dealing.

4.2. Prototye aircraft

If the rig testing has been done thoroughly, little time will need to be spent on the prototype aircraft before flight. This is important because at the time the aircraft is ready for fuel system checks, there is usually frantic activity in preparation for flight and much delay will be caused by the temporary stoppage of other work.

It should be sufficient therefore to:—

(*a*) Check for leaks and obstructions.

(*b*) Check the fuel flow and pressure available at each engine for comparison with rig results.

(*c*) Function all moving units in the systems.

(*d*) Check the tank capacities, unusable fuel capacity, water sump volume and tank air space.

(*e*) Calibrate the tank gauges.

Apart from the tank gauge calibration, these checks are to ensure that the system is conforming to the standard determined from the rigs and that everything is functionally satisfactory.

4.3. Flight tests

Although the information obtained from the rig tests should have given a clear understanding of the behaviour of the fuel systems in flight, it is unlikely in practice that all likely flight conditions have been covered, and there is usually some outstanding data required, or some flight effects which are impossible to produce on the ground. In addition, therefore, to checking the general functioning of the system under all operating conditions, it will be necessary to fill in the gaps of knowledge left from ground tests.

Unfortunately, this last phase in testing may tend to be delayed or forgotten in the urgent necessity to compete with the vast amount of testing in general.

A comprehensive knowledge of the system is essential, to enable troubles which inevitably occur when the aircraft is in service, to be investigated and remedied.

4.4. Fuel temperatures measured at high altitudes

Much testing and theoretical work has been done by such competent authorities as the Royal Aircraft Establishment and Rolls-Royce Ltd., to establish the minimum temperature to which fuel will fall when operating for long durations at high altitude. The conclusions drawn from these tests are that without special insulation provision or

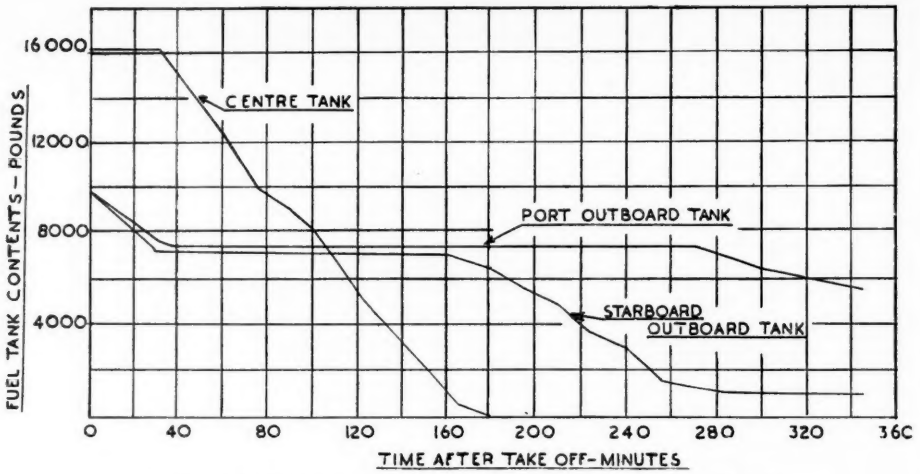

Fig. 21. D.H.106 Comet G-ALVG. Fuel contents during flight on 21-2-50.

heating, the fuel in integral wing and exterior tanks will drop below the minimum to ensure fuel feed and freedom from fuel filter blockage, after some three or four hours' flight. With respect for the warning given by these conclusions, no trouble has been experienced with Comets during their many hundreds of hours of flight. Because of the importance of this aspect of high altitude flying, very careful measurements were made of the wing skin and integral tank skin temperatures, and of the fuel inside.

Figure 20 shows the positions of the fuel thermometers and wing skin thermo-couples used for these tests, and it should be noted that during the flight, temperatures were taken with the port outboard wing tank about $\frac{3}{4}$ full, while the equivalent starboard tank fuel was used to a low level. Thus the effect of full and empty tanks was obtained.

The way the fuel was used is given in more detail in Fig. 21.

The duration of the flight was approximately $5\frac{1}{2}$ hours, of which $4\frac{1}{2}$ hours was spent cruising at altitudes between 35,000 ft. and 40,000 ft. The ambient air temperatures varied between $-55°C.$ and $-66°C.$

Figure 22 shows the temperatures recorded by the wing skin thermocouples and Fig. 23 shows the fuel temperatures.

The results show that:—

(*i*) There is no measurable difference in temperature between the wing skin forming the tank bottom and the bottom skin outboard of the tanks, except that the former does not react as quickly to change of ambient temperature.

(*ii*) The fuel temperature at the bottom of the port outboard tank had stabilised at, or slightly above, the tank skin temperature.

(*iii*) The tank bottom skin maintained a temperature roughly 25°C. about ambient air.

(*iv*) There was considerable temperature gradient through the fuel since a rise in fuel temperature occurs at the bottom of the tank as soon as a tank pump is switched on and causes agitation.

It is hoped that the results taken on the Comet will be supplemented by those taken on other aircraft in the near future. In the meantime it can be said that these tests were most carefully conducted and can be taken as representing the conditions prevailing on this aircraft. Taking the absolute minimum permissible fuel temperature as $-45°C.$ the Comet can fly in temperatures of down to $-70°C.$

The lowest true ambient air temperature recorded by the Comet is $-67°C.$

Temperatures lower than $-70°C.$ are rarely met and are likely to be fairly local. If, however, such temperatures were encountered during the early to mid stages of flight, the mean fuel temperature in the tanks would not have dropped sufficiently to present a hazard.

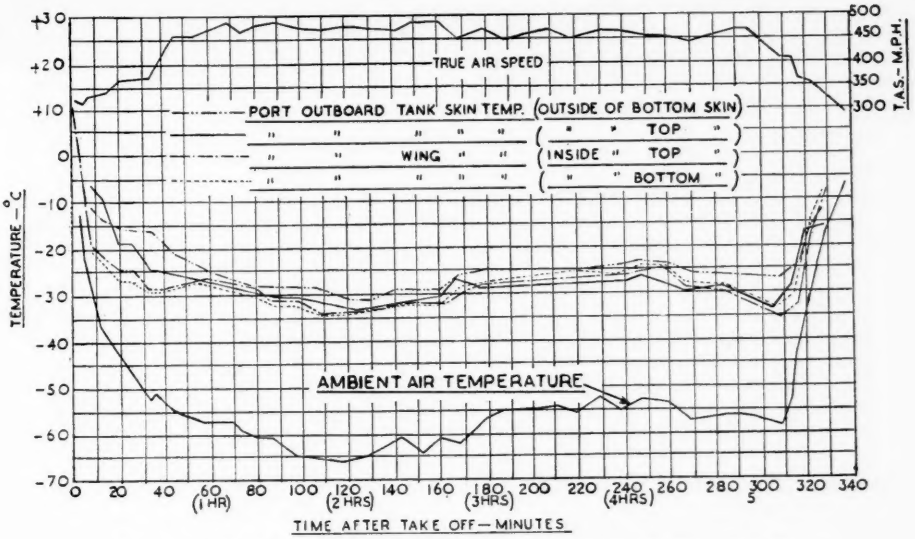
TRUE AIR SPEED
PORT OUTBOARD TANK SKIN TEMP. (OUTSIDE OF BOTTOM SKIN)
" " " " " (" " TOP ")
" " WING " " (INSIDE " TOP ")
" " " " " (" " BOTTOM ")
AMBIENT AIR TEMPERATURE
TEMPERATURE - °C
T.A.S.-M.P.H.
TIME AFTER TAKE OFF—MINUTES
(1 HR)
(2 HRS)
(3 HRS)
(4 HRS)
5

Fig. 22. D.H.106 Comet G-ALVG. Wing skin temperatures in flight, 21-2-50.

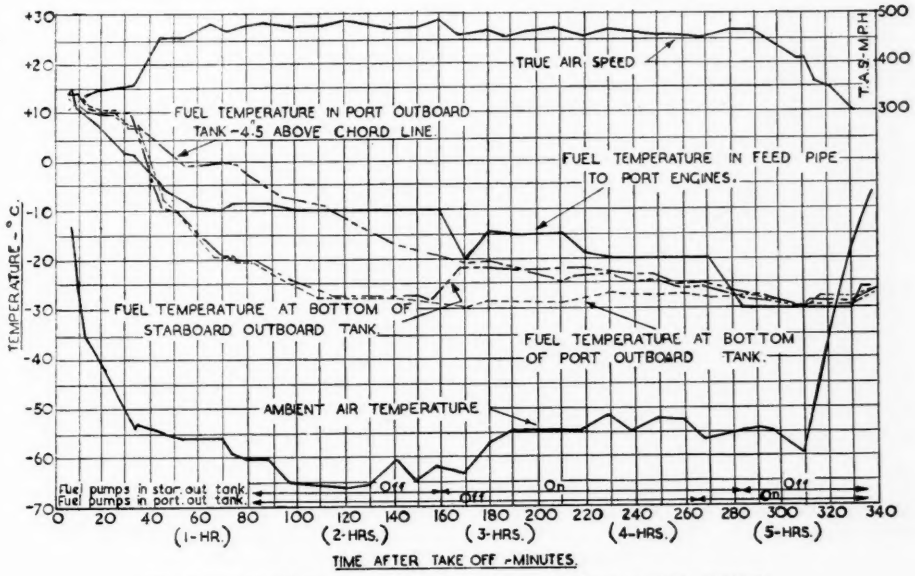

Fig. 23. D.H.106 Comet G-ALVG. Fuel temperatures in flight, 21-2-50.

Fuel feed temperature gauges, however, are fitted to enable the crew to anticipate trouble should the occasion ever arise when, by reducing height slightly, the ambient temperature can be raised the required amount.

A lowering of the specification freeze point of kerosine by 5°C. or more would be a valuable contribution in this respect, and it is hoped that further consideration will be given by those concerned to the possibility of doing this.

5. SUMMARY

Kerosine as a fuel removes the difficulties associated with fuel boiling, but care must be taken that liberated air does not enter engine feed lines.

Wide-Cut gasoline requires tank supercharge if used above 30,000 to 35,000 ft.

Kerosine offers a standard of safety for civil transport which must not be lost in favour of the convenience of using more volatile fuels.

A reduction of at least 5°C. in the specification freeze point of kerosine should be seriously considered.

The development of fuel contents gauges still requires urgent attention to achieve the degree of accuracy necessary.

Integral fuel tanks can be made to work reliably provided that the initial design is given adequate consideration.

Fuel systems are growing in complexity with the present trend in aircraft layout. Early consideration of the problems of fuel feed will help to reduce this complication.

Ground fuelling equipment requires good filtration which can be maintained cheaply and easily.

Systematic and extensive Ground Rig Testing of fuel systems is necessary to reduce flight testing and facilitate early production.

ACKNOWLEDGMENTS

The author is aware that much of the material of this paper is common knowledge among those engaged on fuel systems, and for this reason much detail has been avoided.

On the other hand it is hoped that some experience has been passed on.

The author is grateful to the Oil Companies for their ever-ready co-operation in supplying fuel data and to his colleagues for their valuable assistance in preparing the paper.

Finally, he would like to thank the de Havilland Aircraft Co. for permission to use the facilities and material on which the paper is based.

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DISCUSSION

R. H. Warde (Air Registration Board, *Assoc. Fellow*): He thought that the fuel system for turbine-engined aircraft required a much higher standard of design and installation than had been needed for piston-engined aircraft.

Most people thought kerosine presented a smaller fire risk in aircraft than gasoline, both from the possibility of fires in the air and for a crash landing. He believed that this general view was inclined to overshadow one feature of kerosine which, if not carefully observed, might result in the actual possibility of fires in turbine-engined aircraft in flight being higher than the average for piston-engined aircraft using gasoline. It had been proved several times in aircraft in flight, that kerosine did not evaporate easily and therefore any of this fuel which was spilt, either outside or inside the structure of an aircraft, remained there for a long time and only required the right conditions to cause a serious fire. The lesson to be learnt from this from the point of view of fuel systems was careful design of all vents and drains, and thorough ventilation of all compartments adjacent to items containing kerosine fuel.

Mr. Walker had referred to the use of Wide-Cut gasoline in civil aircraft. After careful consideration of all the available data on the fuel generally described as J.P.4, the Air Registration Board had strong preference for kerosine as the only fuel suitable for turbine-engined aircraft. The Board had an open mind on this subject but until further data existed and satisfactory tests had been completed, any recommendations for a Certificate of Airworthiness must at present be confined to those aircraft using kerosine as fuel.

He did not think Mr. Walker had made a strong enough case for the essential requirement that the fuel system for turbine-engined aircraft must, at all times and under all conditions of flight, deliver sufficient fuel to the engines at a positive pressure. The most important reason for this was that the combustion of turbine engines was susceptible to extinction following an interruption in the supply of fuel. Unlike the piston engine many turbine engines did not automatically restart when the fuel flow was restored and this, associated with the difficulty of relighting at altitude, dictated the necessity for a continuous supply of fuel at the correct pressure.

It was felt that even on civil aircraft, provision should be made for the satisfactory functioning of the fuel system under conditions of negative *g* for a period of between 5 and 10 seconds.

He thoroughly agreed that it would pay to do as much rig testing of turbine-engined fuel systems as possible. In the past there had been a tendency to view the average aircraft fuel system as a collection of tanks and piping which, if all went well, would deliver some fuel in an unknown condition to the engines. The de Havilland Aircraft Company should be congratulated on the comprehensive rig testing which had been done on the Comet fuel system, and he looked forward to similar tests being made for other types of aircraft. If this were done he hoped that there would be a free exchange of information, as it was tragic to see one contractor making new discoveries as a result of certain tests and withholding the information from the rest of the Aircraft Industry, even to the extent of actual accidents taking place because of the lack of information.

M. O'Farrell (Shell Aviation Department): A particularly interesting feature of the temperature measurements was that they showed the theoretical kinetic heating effect to be valid in practice, in this case about 25 degrees at 500 miles an hour. However, it was unfortunately apparent that this was not enough by about 5 degrees, which was interpreted as a deficiency in the fuel. He thought another interpretation might be that it was rather a pity that a magnificent aircraft like the Comet should be only 50 miles an hour too slow for the fuel it was designed to use!

Kerosine was established as a fuel long before the gas turbine was thought about, and it was rightly chosen as the best fuel for the aircraft gas turbine because it was a standard product of relatively low viscosity and high flash point. Civil operators would benefit during the period when their up-take of fuel was negligible, by the use of the already established distribution system for the product. To propose a lowering of the freezing point, or for that matter any other restriction in the specification, was tantamount to asking for a special fuel, with all

the extra cost that that implied. He suggested that Mr. Walker should defer his demand for that requirement until the amount of fuel used by civil gas turbines was sufficient to justify the distribution of a separate grade of fuel. Also he advised against demands for control over such things as specific gravity, because they would be restrictive and would have a tendency to increase the price of the fuel. In the meantime, if the aircraft could not avoid those fortunately rare extremes of low temperature, perhaps some slight degree of heating could be applied to the fuel system.

Water and dirt in the fuel was a perennial problem with which the oil companies had always to contend. A most elaborate system of protection, involving settling, water draining, filtration and micro-filtration, had been built up. He thought Mr. Walker would find that all the recommendations which he could put forward were already being put into effect and had been so for years. It could not be too greatly stressed that water would accumulate in aircraft fuel tanks. That this was inevitable had now been generally accepted.

The author had pointed out that one pint per thousand gallons was likely to come out of solution; to this could be added half a pint per thousand gallons due to condensation in the air space, and possibly some more for precipitation water coming through the vents.

He had been fortunate enough to examine a Comet aircraft as it returned from a long flight, and the condensation on the outside of the aircraft was quite spectacular. Presumably condensation of the same sort was occurring on the inside of the tanks, where the temperature and atmosphere were similar. A total accumulation of about a gallon of water in the fuel was thus possible on every flight. That such amounts had not been found meant that the water had been digested by the engine. However, tests quoted in the paper showed that in certain circumstances it could be deposited on the filter as ice and interrupt the fuel flow. Until more information was available on this phenomenon, that possibility had to be taken into account. A remarkable fact was that a very small amount of dirt or water could shut down one of those powerful jet engines, which seemed absurd; was any effort being made to persuade the engine manufacturers to reduce the watch-like sensitivity of their fuel systems to minor contamination.

It was mentioned in the paper that high calorific value per gallon was preferable. A high calorific value per gallon implied a low calorific value per pound. Did the statement apply to civil as well as to military aircraft, because hitherto high calorific value per pound was thought to be more important on civil aircraft, on the principle that fuel + payload was constant for a given range, and the less the fuel load the more the payload and the more the money earned. He would have thought that the same thing applied to the Comet, except for extreme range of operation.

J. C. King (English Electric Co. Ltd., *Assoc. Fellow*): Had Mr. Walker any experience of the phenomena of fuel bumping in which the vapour released was delayed until the pressure was lower than that at which the vapour would normally be released if agitated? This was apparently unlikely in a tank in which a pump was running, but in a tank not in use it might occur and lead to high shock pressures unless large vents were provided. The problem did not occur in a system adequately pressurised to prevent boiling, but could be worrying in using emergency fuel of high R.V.P. in a system designed to allow the vapour to boil off.

If laboratory reports were to be believed it was a problem to which more attention should be paid. He would welcome Mr. Walker's views.

In one matter he would go further than Mr. Walker and make a plea for a 1/16th or smaller scale model of a fuel tank before the structure and baffles were settled. His firm had done that and it was surprising how useful it could be. It could be made up in ten hours instead of ten days or ten weeks.

He would also make a plea to all engine manufacturers to standardise on the pressure required at the engine pump inlets on all turbine engines so that engine changes from one type to another in a given aircraft did not involve a re-designing of the aircraft fuel system.

C. F. Holloway (Technical Adviser, B.P. Aviation Service, *Assoc. Fellow*): It should be remembered that the kerosine used at present for aviation turbine fuel, which was controlled by the Ministry of Supply specification DERD 2482, was a product made and marketed universally by the oil companies and was normal lighting kerosine or lamp oil. There was no real difficulty, therefore, in supplying relatively small extra quantities of this fuel wherever they were needed in the world.

When additional specification requirements were introduced, such as the lowering of the freezing point by 5°C. or the inclusion of a permittivity clause, then the kerosine became a special product and had to be refined, transported and stored as a separate product with all the additional difficulties of segregation throughout the distribution system and, because of the small quantities involved (it would only be needed for commercial turbine-engined aircraft) it would of necessity carry a price premium. Also, when restrictive clauses were added to a specification they would obviously reduce the quantity which could be made available from the crude oil. In general there was no difficulty in producing a special product but the overall economics must be borne in mind.

Mr. Walker had said that filters became blocked by solid hydrocarbons at −45°C.; could he give the actual freezing point of the fuel used during the tests? He seemed to recall a figure from Rolls-Royce that only partial blockage of the filter occurred at −47.5°C. and if a filter by-pass were fitted the system would remain operative down to −54°C.

Free water pumped into an aircraft from a fuelling vehicle was an unforgivable sin. Fuelling of commercial aircraft was usually undertaken outside the United States by oil companies and very strict quality control regulations were laid down. All their fuellers were checked daily for water by draining the tank sumps. If any fueller were reloaded at the aerodrome installation it was not permitted to deliver fuel to an aircraft until it had remained stationary for a period and been checked again for water.

It was well known that fine solid particles (usually rust particles) had an affinity for water but this was taken care of by installing on all fuellers delivering aviation turbine fuel and practically all fuellers delivering aviation gasoline, approved fine particle filters which would remove all solids down to a particle size of 10 microns. The variation in fuel characteristics which the Comet had met *en route* to Africa and the Far East should all have been within the specification limits as once again the quality control regulations would search out and eliminate any off-specification fuel at all points of the distribution system.

The capacitance type of gauge for measuring the actual quantities of fuel remaining in the tanks relied basically on the permittivity value of the fuel. He believed that the variation of this value for aviation gasoline had been found by the Royal Aircraft Establishment to be of the order of 11 per cent., and his own investigation had shown even this figure to be conservative. He did not know the range which would be applicable to Wide-Cut gasoline but he anticipated that it would have at least as wide a variation as that of aviation gasoline.

Would Mr. Walker give some idea of the pressure limitation of the under wing system? He understood that with the Comet the system was designed for a maximum of 30 lb./in.^{2}; would it be possible for the full fuelling rate of 200 I.G./min. to be attained without exceeding this figure?

L. F. Campion (Ministry of Supply, *Assoc. Fellow*): The rig illustrated in Figs. 4 to 7 demonstrated the effect of temperature and altitude, but the figures quoted were somewhat misleading as were all results from a rig which recirculated the fuel. Under such conditions the fuel weathered considerably because of the repeated testing, and the vapour pressure fell to a very low value and must have done in this case to have given the figures quoted. With fresh fuel the conditions were much more serious and at 50°C. a fuel at the top limit of 3 lb./in.^{2} R.V.P. started to boil at 29,000 ft.

The use of the booster pump to prevent cavitation of the engine-driven pump was being exploited by the engine designers and was being used to cover deficiencies in the engine pumps. In some cases engine development resulting in greatly increased fuel requirements had rendered the original pumps totally inadequate, unless supercharged to a high figure, and a larger pump should have been fitted. For these reasons the minimum permissible engine pump inlet pressures were steadily rising and, together with the higher pressure drop across the L.P. filter with increased flow the position was being reached when even under emergency conditions an engine would not be able to function at any altitude without a booster pump, or if the pump had failed. Advantage could not be taken of the possible reduction in booster pump pressure at low altitude since that was the time when the required engine pump inlet pressure was at its maximum.

It should be possible for the airframe designers to persuade the engine designers to incorporate a gear or vane type pump on the engine to supercharge the metering pump through the L.P. filter. Advantages of such an arrangement would be that smaller booster pumps could be fitted, with a saving in weight and current consumption; the L.P. filter could be smaller with a higher permissible pressure drop; the agitation of fuel before entering the filter would assist in the filter icing problem, and the failure of a booster pump would be less serious.

E. B. Moss (*Assoc. Fellow*): Mr. Walker's plea for increased accuracy had not fallen on deaf ears. He thought they had to confess that in that instance aircraft constructors' ideas were ahead of theirs and their experience. He thought they would change that, possibly progressively, but it must be realised that they were now not just putting an engine into an aeroplane. Taken by and large it was a number of components which together made up a system and as a system its success depended on co-operation between the makers—the specialist who made the engine and the aircraft constructor. Their experience was that such success as they had had resulted from that type of co-operation.

N. E. Rowe (Blackburn & General, *Fellow*): He would like to add his congratulations to the Luton Branch on attaining their tenth anniversary and for all the good work that they had done. He also thanked the Branch Chairman and the executive officers and staff for the work that they had put into the organisation of the meeting.

Mr. Dowty had mentioned that he had been impressed by the enthusiasm of the Branches. That was one of the things which impressed him also. It always gave him a great deal of pleasure to go to a Branch and see so much enthusiasm, and especially the enthusiasm of young men. In a sense the Branches could touch a much wider field than the main Society and in that way could inform and maintain the interest of a much wider body of opinion. The Branches, he hoped, were also a place where the young men of the Society could say their piece, feeling that they were at home in doing so.

He liked to think that the Branches were a useful recruiting ground for the main body.

As the Chairman had reminded them this was one of the occasions when the main Society came to the Branch. It was the eighth or ninth main lecture that had been held at a Branch and they had all been uniformly successful. He thought they did a great deal of good.

The lecture that night had been on an important subject which was going to become increasingly important as more onerous conditions were reached by the use of turbine engines in aircraft.

He had been impressed by the way in which the oil companies had said their say, and by the way in which Mr. Walker had said "Well, for an aeroplane we want the best, and nothing but the best, and we want you to provide it." He thought they would.

P. E. Felgate (*Assoc. Fellow*), *contributed*: Referring to the capacitance, or dielectric type fuel gauge, the author had drawn attention to the necessity of having data on the permittivity and specific gravity of the fuel. Mr. Holloway had referred in the discussion to a Royal Aircraft Establishment Report, quoting that the permittivity of different fuels tested by the R.A.E. varied over a maximum range of 11 per cent. It should be noted that this figure was the maximum difference between kerosine and petrol fuels.

Variations in the permittivity and specific gravity might affect the accuracy of the fuel contents reading, but the extent to which the accuracy was affected would depend on a number of factors, and particularly on whether the gauge was calibrated to indicate volume of fuel, or mass of fuel. For a gauge calibrated in terms of mass of fuel, the errors due to changes of fuel were considerably less than the corresponding ones if the gauge were to indicate volume. This resulted from the relationship which existed between permittivity and specific gravity of the fuel.

For a fuel gauge such as was used on the Comet, calibrated to indicate mass of fuel, the effect on the gauge reading of differences in the fuel was not as large as might appear directly from the figures in the paper and those discussed. The Comet was using kerosine to DERD 2482. Considering the variations of samples of kerosine to the same specification it turned out that the maximum effect those would have on the accuracy of the gauge (which was calibrated to read in mass) was ± 0.7 per cent. of the indication.

E. L. Carlisle (*Associate*), *contributed*: He thought that dirt and water in the fuel were

going to give the most trouble to operators, whether civil or military.

Trouble with dirt in the fuel causing malfunctioning of the engine servo mechanism was still being experienced, and although filters were designed to function down to 12½ microns, it was difficult to believe that they did so efficiently.

Mr. Walker mentioned that the Comet had had throuble because of blockage of the low pressure filter by particles of ice, and that the conclusion was that free water had been inadvertently introduced into the tanks; this was despite the fact that the refuelling operation had been done at their premier airport where stringent control was exercised.

What would happen to squadrons of military aircraft refuelling in a hurry under conditions of emergency at forward airfields?

Mr. Walker said that one method of overcoming filter icing was to provide a filter bypass; this was the easiest solution from the aircraft designer's point of view, but it ignored the engine man's headache of dirty fuel passing into the system, and he would suggest the anti-freeze or heating methods in preference.

He wished to echo Mr. Walker's plea about flexible hoses, particularly engine high pressure hose. The engine flexible fuel pipes had to operate in high engine bay temperatures at high internal pressures and also, had to withstand high soak temperatures when the pipes were empty; although reasonable serviceability was already obtained, those pipes were so important and had to do such a strenuous job that work should never stop on seeking ways to improve them.

E. S. Allwright (Vickers-Armstrongs Ltd., Weybridge, *Assoc. Fellow*), *contributed*: The advantages of kerosine fuel had been clearly indicated. Its greater density provided the opportunity for carrying the maximum weight of fuel in the least amount of space, and the increased safety due to its low volatility could not be over-emphasised. Every effort must be made to continue the use of kerosine in all civil aircraft, and as much as possible in Service aircraft.

The capacitance type of gauge used in kerosine tank systems was demonstrating a high degree of reliability of operation, but the degree of accuracy which could be obtained at present was not enough and further developments were needed urgently to reduce the effects of temperature changes, differences of fuel and unit variations.

Some of the difficulties had been mentioned of finding a satisfactory position for the cut-off switch in pressure refuelling systems, but an additional problem was to find a position where the quantity of fuel in the tank when the switch operated was unaffected by the attitude of the aircraft on the ground, or the slope of the ground itself. The greatest problems occurred with large flat shallow tanks, or with tanks or inter-connected tanks, extending spanwise for some distance.

The design of an aircraft refuelling system was closely bound up with the design of the refuellers which would service the aircraft. It was a necessary precaution to install pressure relief valves in the tanks to prevent an excessive build up of pressure if the cut-off devices failed to operate, but this was only effective provided that the rate of refuelling was not greater than the flow for which the relief valves had been designed. It must be remembered that there would probably be no visible external sign of structural damage due to excessive pressures in the fuel tanks. Some means of preventing excessive rates of refuelling was required. One way to do this was to arrange that the maximum delivery line pressures of all refuellers were the same, possibly 45-50 lb./in.^{2}, and to design the aircraft piping so that when this maximum pressure was provided, the rate of flow was the greatest that could be accepted. This type of design, unfortunately, meant that the refueller pumping system was always working at its maximum pressure for full flow.

A more attractive method was to provide valves in the delivery lines which would control the rate of flow of fuel and when these valves were pre-set to the maximum allowable for the aircraft, then this would not be exceeded under any conditions of pump r.p.m. or delivery pressure. A dial indicator showing the rate of flow, and positioned conveniently to the refueller operator, should enable a satisfactory check to be made on the automatic controlling valves.

Dr. E. W. Still (Teddington Controls Ltd., *Assoc. Fellow*), *contributed*: The paper disclosed the first public information on the new fuels for jet engines.

Initially all jet engines were designed to use kerosine and it was only later that it was found that there would be inadequate supplies available if this were to be the only

fuel. In the intervening time a large number of aircraft had been designed on the assumption that wings would not be subject to the stresses set up by boiling fuel resulting from pressurised tanks.

It became necessary first to revert to gasoline for military purposes and tanks were then found to be unable to withstand large pressure without considerably increasing the wing structure weight. The fuel to which reference was made was the original gasoline of 7 lb. R.V.P.

In order to reduce the wing structure weight as much as possible the new Wide-Cut gasoline was developed with an R.V.P. of 2 or 3. While this new fuel might be available in quantity it was to be hoped that it would not be used for civil aircraft in view of its increased fire and explosion risk. A study of its characteristics as given in the paper would show that kerosine was normally below explosion level in flight and 7 lb. fuel above it, but the new Wide-Cut gasoline was right in the flight explosion range.

The fall of fuel temperature quoted for the Comet was for integral tanks. Would not a change of temperature be much less for bag tanks? The author seemed to consider $-45°$ a satisfactory minimum fuel temperature. Was it not true to say that altitude air temperatures in the tropics might go well below $-70°$C. at 50,000 ft. so that there would seem to be little or no margin when talking in terms of $-45°$C. as the minimum fuel temperature? The tropopause hardly existed, the temperature lapse rate still dropping by 2°C. per 1,000 ft. up to an altitude of over 60,000 ft.

Among many other interesting points the paper made it clear that for military purposes jet engines had given no let-up on the necessity for pressurising fuel tanks to prevent fuel boiling, or for taking adequate fire prevention steps, as the new fuel was an even bigger risk than its last war counterpart.

F. E. S. Smedley (Rolls-Royce Ltd.), *contributed*: Mr. Walker had covered his subject so thoroughly and comprehensively that there was little which could be done but to support the views he had expressed, except in the few instances where rig test work carried out at Rolls-Royce had not agreed exactly with flight experience on the Comet, or where points raised during the discussion called for special comment.

The need for a comprehensive series of rig tests before the aircraft flew could not be over-emphasised. It was most unlikely that some of the snags which were detected by such tests would ever have been foreseen by any amount of theoretical study or examination of drawings beforehand. The tank venting system should also be rig tested thoroughly, the tests where possible to include altitude rig checks to check tank pressurising during climb, and to investigate the possibility of depressions during rapid descent.

Mr. Walker stressed the need for the use of full bore components throughout the entire low pressure fuel feed system. This was most important, particularly now that turbine engines had to be cleared for operation on fuels of high volatility and to be able to regain base in the event of a booster pump failure. In certain cases it had been found that the type of component used in the fuel feed system had had a far greater effect on the overall restriction to flow than had the nominal size of the feed pipe. In one case in particular, the restriction of a system was reduced to less than a quarter of its original value, merely by replacing restricted L.P. cocks by full bore units and by deleting sources of local restriction caused by abrupt changes of section and direction, but without any increase in the maximum bore of the system.

Mr. Walker referred to the tests which were made by Rolls-Royce to investigate filter icing and which had shown definitely that this danger existed. The Comet aircraft had only run into trouble on one occasion through filter icing and this had been found to be due to the admission of free water to the tanks during refuelling, and it was felt that the rig tests did not truly represent flight conditions.

The later tests made by Rolls-Royce reproduced exactly the conditions of cooling which would occur in flight, the rate of cooling actually recorded during the Comet flights being used in certain cases, and erratic results due to the admission of humid air into the fuel tank were avoided by venting the tank through a dehydrating agent. The actual filter used on the Ghost engine was used for several tests to remove any possible differences in the ice blocking characteristics of filter elements. Micronic refuelling filters were used, and dissolved water contents were normal.

The only explanation for the difference between the rig tests and Comet flight test results was that the tank sequencing drill might have accounted for this. The Comet took off and climbed on the integral wing tanks and then turned over to the centre-section tanks, the contents of which were then consumed completely. During this part of the flight the wing tanks were subjected to intense cooling, but when the engines were turned over to these tanks again it was possible that the quantity of really cold fuel used before the end of the flight was not sufficient to build up a serious deposit of ice on the filters themselves. It was possible that, with any increase in duration of flight, trouble might be experienced due to the water originally dissolved in the fuel as well as to any free water which might get in during refuelling.

Again, rig tests by Rolls-Royce, including measurement of the rate of cooling of fuel in typical aircraft tanks, had shown that the danger of filter blockage due to wax separation would exist on an aircraft such as the Comet.

Many flight trials on this aircraft had shown that the lowest temperature reached was some 3°C. above the specification cloud point of the fuel, although the lowest extremes of air temperature had not yet been encountered. Furthermore, the phenomenon of a temperature rise on the aircraft wings greater than $(V/100)^2$, even in positions where the effect of the sun would have been negligible, merited further investigation, as did the rather unexpected speed with which the fuel temperature followed any change in ambient air temperature.

It would be interesting to know whether there had been any evidence during the flying on the Comet of rapid wear of the brushes in these pumps, which might be expected in view of the similar trouble experienced on other electrical components at high altitude.

Mr. Campion had mentioned the possibility that the sample of fuel used for the demonstrations might have been weathered due to its comparatively high initial boiling altitude. Figures of the boiling altitude of this fuel had been rather conflicting, but the results of all tests so far undertaken by Rolls-Royce had shown a lower boiling altitude than those quoted by the lecturer.

Both Mr. King and Mr. Campion criticised the stringent inlet pressure requirements of modern turbine engines. It would be difficult to meet Mr. King's requirement of a fixed minimum inlet pressure for all types of turbine engines to avoid changes in the aircraft low pressure system when a change in engine type was made, as this would mean using a different size of engine filter, pipe system and high pressure pumps for every change of engine rating. The most that could be offered would be to fix a top limit for minimum inlet pressure which would never be exceeded on any engine type, but this might not mean the most efficient installation for any given aircraft/engine combination.

Mr. Campion had said that the very high minimum inlet pressure required by jet engines was an imposition on the aircraft designer and necessitated the use of booster pumps much larger than would otherwise be required. To avoid this would involve an increase in size and weight of the engine-carried suction fuel system which would have to be assessed alongside the increase in booster pump size which the present requirement involved. Furthermore, on axial flow engines, it was difficult to increase the size of the engine-carried fuel system without increasing appreciably the overall diameter of the engine—a serious matter on high speed aircraft which might embarrass the aircraft designer quite as much as an increase in booster pump weight. Mr. Campion also recommended the use of a simple positive displacement pump on the engine, on to which the aircraft system would pick up, and which would have a good performance under suction and keep the rest of the engine fuel system always under pressure. This measure was recommended to the Americans in 1947 to enable them to meet the U.S. Navy's stringent requirements for operation on gasoline fuel with booster pumps off, and was incorporated on the Pratt and Whitney version of the Nene engine. This requirement laid down that the aircraft must be capable of climbing to 8,000 ft. at maximum r.p.m. on gasoline fuel of 7 lb./in.^{2} R.V.P. at 100°F., and with the emergency pump isolation system in operation.

No such official requirement existed in Great Britain, and in any case it was only fairly recently that emphasis had again been laid, officially, on the necessity to operate turbine engines under suction conditions, and the A.P.970 requirements still did not make it clear that a suction test was essential in the pre-flight flow test of an aircraft fuel system.

All practicable steps would be taken to ease both the maximum and minimum inlet pressures required on turbine-engined aircraft, but it would be almost impossible to incorporate the simple backing pump, suggested by Mr. Campion, on a modern high power axial compressor engine. The only way in which this could be provided would be to mount it near the engine in the final airframe feed pipe.

MR. WALKER'S REPLY

Mr. Warde: Although the comments about fire risk in the power plant were, perhaps, outside the scope of the paper, Mr. Warde was right in pointing out that adequate fuel drain control and ventilation were of primary importance.

The fact that kerosine did not vaporise easily from a cold surface was an indication of its safety, but in warm or hot compartments good ventilation was necessary to carry away fuel vapour which would always be present until completely dry engines were available.

The statement about the attitude of the A.R.B. towards the use of J.P.4 for civil aircraft was a very welcome and wise one, since there had been much speculation on this subject.

On the question of fuel feed to the engine, a curve of minimum permissible absolute fuel pressure at the engine pump inlet against fuel flow was required by the aircraft fuel system designer, and values given would depend upon the design of the particular engine pump.

Engine pump inlet pressure demands were tending to become high, because it was thought that tank booster pumps would supply this demand, but this might not always be so. Trends in the shape of future military aircraft might necessitate a reversion to air or inert gas displacement feed where wing strength would limit the permissible pressure Extinction of the engine due to lack of fuel pressure had not been a serious hazard in his experience, the main danger from lack of pressure being damage or reduction in life of the engine pump.

Special provision for negative *g* feed on the Comet had not proved necessary, and there did not appear to be any grounds yet for considering that it would be on large civil jet aircraft.

Mr. O'Farrell: While acknowledging the truth of what Mr. O'Farrell said about the past and immediate availability of kerosine, and the effect of this on cost, it must be emphasised that the function of the civil aeroplane was to convey payload and every item added in the way of equipment, such as fuel heaters, meant a reduction in the commercial value of the aeroplane. It might be that the cost of fuel of lower freeze point would increase but this must be balanced against the first cost of the heating equipment, the loss of revenue due to the added weight, the loss in power plant efficiency necessary to supply the heat, and the additional maintenance costs.

Taking into consideration the time required to manufacture or select a fuel of lower freeze point and arrange for distributed storage, no time could be lost in making a start, and it should be quite possible to predict future civil demands.

Within certain limits it was doubtful whether the degree of filtration had any bearing on the susceptibility of a filter to ice up under the exceptional free water condition quoted. On the other hand, coarsening the filtration would be of benefit in ensuring that ice formed from the normal water content of the fuel could pass without clogging, as it would appear to do now. On the question of whether the calorific value of a fuel should be related to weight or volume, it was true to say that practically every aircraft had at some time to find room for additional fuel, and more heat per gallon would give relief.

Aircraft operating with tanks less than full would benefit from an increase in heat value per unit weight of fuel. However, the tare weight of the aircraft was influenced by the volume of tankage, and since aircraft were designed to meet a certain range specification, this was most economically achieved by the use of a fuel of high heat value per gallon. An improvement on either basis would be valuable, provided that it was not at the expense of the other.

Mr. King: He had had no experience of fuel bumping, probably because agitation in the fuel tank had prevented the delayed release of vapour, but the possibility of such a phenomenon should be kept in mind.

It had been noticed on altitude rig tests that, without agitation, the release of air from kerosine was delayed and then released suddenly at about 22,000 ft.

It was interesting to hear that Mr. King had also found small fuel tank models valuable. He hoped the pump manufacturers would give every consideration to his suggestion of standardising engine pump inlet pressure.

Mr. Holloway: Mr. Holloway had made a good case for leaving the kerosine specification as it was now, but it was difficult to understand why, by applying his arguments, piston-engined transport aircraft were not expected to run on commercial motor fuel.

Unfortunately it was not possible to establish the actual freeze point of the fuel which caused filter blockage during the tests mentioned, but it would appear that different batches of kerosine varied considerably in their freeze point. With the present specification initial freeze point of $-40°C$ it would not be safe to assume that the fuel temperature could be allowed to fall more than a degree or so below this.

The description of the precautions taken to prevent the ingress of free water into aircraft tanks was a welcome one, but was it certain that those precautions could be observed by all fuel suppliers throughout the world?

It was doubtful whether a fuelling rate of 200 Imp. gal./min. could be achieved without exceeding a pressure in the aircraft distributing line of 30 lb./in.^{2} on the shut down of the tank valve, unless a special pressure control valve were used. Such a device had been made and was being used successfully with Comets now operating. (This 30 lb./in.^{2} was a steady "no flow" pressure, and distinct from the instantaneous surge pressure, which was about 50 lb./in.^{2})

Aircraft designed in the future would no doubt be capable of taking pressures up to 50 lb./in.^{2}

Mr. Campion: It was correct that the fuel used for the test was to some extent weathered and did not represent the worst case. Fig. 3, however, gave the results to be expected from fresh fuel.

Tank booster pumps were by way of being like the motor car, introduced as a convenience, and then becoming a necessity which it was not at all certain they could afford. Let the demands be modest, and they could continue to enjoy their benefit.

Mr. Moss and **Mr. Felgate:** When using kerosine only as a fuel, it appeared that errors in fuel gauge reading due to variations in specific gravity of the fuel were of a minor nature, compared with the errors which could occur with wide temperature changes, provided that, as Mr. Felgate pointed out, the gauge was calibrated in terms of mass. On the other hand, Wide-Cut gasoline with its much greater specific gravity range, presented a considerable problem in cases where accurate fuel gauging was important, and it was not at all clear how this situation was to be dealt with, unless, by the fitting of sampling condensers the gauge could be adjusted readily after each fuelling operation.

Mr. Carlisle: While the one case of filter freezing did occur on a Comet operating from an airport where strict control was exercised, the particular circumstances were such that it would not be fair to assume that contamination occurred while under this control. Rigid control of fuelling, such as outlined by Mr. Holloway, should eliminate the possibility of a repetition of this incident.

Mr. Allwright: Not long ago the general complaint was that fuelling units would not deliver at a high enough rate, now Mr. Allright complained of too high a rate, which showed good progress.

Fuelling at 200 gal./min. per tank should present no difficulty, provided that shut-off pressures were not excessive, but it was clear from Mr. Allwright's comments that there must be close co-operation between those persons responsible for the design of the fuelling unit and those designing the aircraft system.

Rather belatedly, standardisation of fuelling couplings had been achieved; now discussion on standardisation of fuelling methods might be opportune.

Dr. Still: The rate of change in fuel temperature with bag tanks was less than for integral tanks; the benefit to be gained by this depended upon the duration of flight and the fuel temperature at the start of flight. With aircraft of long duration it was doubtful whether any benefit would result towards the end of a flight from the use of bag tanks of the liner type. Experience on filter blockage tests indicated that with kerosine to DERD/2482 there was a sharp rise in the filter pressure drop when the fuel temperature reached $-45°C$, which, by adding the

outside air to wing skin temperature rise of $-25°C$ given in Fig. 23, would correspond to an air temperature of $-70°C$.

The series I Comet was not operating above 40,000 ft. and had not experienced air temperatures below $-68°C$ for any serious length of time, although $-73°C$ had been recorded.

Future jet aircraft would operate above 40,000 ft. and air temperatures were likely to be below $-68°C$ more often and for longer periods.

Dr. Still was right in saying that $-45°C$ left no margin for future development, but this would provide a margin for existing Comet I operation.

It should be pointed out that the specification stated the initial freeze point, that was the temperature at which solid hydrocarbons first appeared, and it would seem from test that solidification, sufficient to cause filter blockage, occurred at 4 to $5°C$ below this point.

Mr. Smedley: Mr. Smedley suggested that there might be partial blockage of the filters by ice from dissolved water in the fuel, and any free water normally present. If this were so, either ice on the filter or water in the bowl would be found on examination immediately the engines were stopped after the aircraft had completed a flight of long duration. Many examinations of this nature had been made, and no evidence of ice or water accumulations found.

Examination of Fig. 22 showed that there was no obvious difference between the top and bottom wing surface temperatures. The sun therefore, did not appear to have any heating effect. In the case where fuel temperature reacted rapidly to change in ambient air temperature, the thermometer was very close to the bottom tank surface and the fuel was undisturbed.

Rapid wear of booster pump brushes had not been apparent, and it was possible that a kerosine film on the rubbing parts provided sufficient lubrication.

The Influence of Tyre Pressure on the Design of Aerodrome Pavements

by

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1. INTRODUCTION

The influence exerted by the technical development of a vehicle on the design of the surface on which it travels is of considerable historical and social importance. Technical progress in the design of the road vehicle has never been matched by a similar development of the road, and in the past 50 years the discrepancy between the performance of the vehicle as dictated by road conditions, and the performance of which it is capable has been even more marked. The policy, forced upon society by national and international conditions, of compelling the vehicle to conform to the present standards of road design is highly restrictive and uneconomic, and such devices as pedestrian crossings, traffic lights and speed limits, are all evidences of failure to solve the problems of the simultaneous development of vehicle and road.

The parallel relationship between the aircraft and its running surfaces is, by comparison, relatively unfettered. This is due chiefly to the tacitly accepted principle that the vehicle should not be limited in development by the design of the surface on which it operates. Up to the present, the performance of aircraft has not been restricted by the existing state of runway or perimeter-track design. The assumption has been made that the civil engineer will provide an adequately strong and suitably surfaced track for whatever aircraft are designed. Whether this expansion can continue is a question of some importance.

When aircraft were developing rapidly during the Second World War the civil engineer had many new problems to face and many runway failures to study and explain. He was forced, by the abnormally accelerated rate of development of the aeroplane, to work far outside his usual experience of loadings on road surfaces. Fundamental principles which had dropped out of sight through being accepted as axiomatic, or had been disregarded and forgotten, were once more studied objectively. The significance of the quality and properties of the subgrade, and the immense importance of the moisture content of the soil were seen in a new light.

"The erroneous opinion so long acted upon, and so tenaciously adhered to, that by placing a large quantity of stone under the roads, a remedy will be found for the sinking into wet clay, or other soft soils; or in other words, that a road may be made sufficiently strong, artificially, to carry heavy carriages, though the sub-soil be in a wet state, and by such means to avert the inconveniences of the natural soil receiving water from rain, or other causes, has produced most of the defects of the roads of Great Britain."

This extract, which reads like the findings of some modern research in soil mechanics, was written in 1821 by John Loudon McAdam the pioneer road builder, and is a tribute to his sagacity and penetrating observation. Only in recent years has the truth of his statements been wholly accepted.

So far, the civil engineer has kept pace with the development of the aircraft and has been able to provide pavements suited to each new development. However there have been signs in recent years that still higher standards of performance in the aircraft will present formidable problems to the civil engineer. In his address to the British Association at Edinburgh in August 1951 on "Some Social Consequences of the Aeroplane" Dr. E. Warner promised "a vastly increased speed" and pointed out that man may expect a "new chapter of possibilities to add to the far-reaching possibilities that the aeroplane has already given him." The civil engineer feels competent to deal with these vaguely threatened developments, but whether the provision he can make for land

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aerodromes is the best solution to the problem is a topic for consideration. If longer runways of deeper construction become common or necessary, the possibilities of arrester gear, assisted take-off, and the use of flying boats for the largest loads may be considered. Such changes have been suggested on various occasions, but their consideration is outside the scope of this article.

The problem presented to the civil engineer at the moment is twofold. Firstly, he must plan the aerodrome and its airport facilities for two-dimensional flow of traffic. Lengths and widths of runways, layout of taxiways and aprons and the location of airport buildings all receive consideration under this heading. The second problem is that of the provision of an adequately strong runway whose surface is neither damaged directly by traffic nor suffers damage due to failure of the subgrade.

These two problems are apparently unconnected, but the first influences the second. Class A aerodromes on the I.C.A.O. classification require a main runway of 8,400 ft. Combining this requirement with those of the provision of clear flightways and accessibility to large centres of population, the airport designer finds himself restricted to relatively few useful sites for the more important airports. To add to the already formidable list of requirements, that of a strong foundation soil would make the problem of aerodrome location very hard indeed. Aerodromes must often be founded on whatever subgrade occurs at the most desirable sites, and many of the technical problems faced by the civil engineer during the war were concerned with supporting the increasing intensity of loading on what often appeared to be a decreasing acceptability in foundation material. As wheel loadings, and particularly tyre pressures, continue to increase, the problem of providing adequate runway strength demands a more closely reasoned knowledge of fundamental principles and a more strict control of construction operations.

2. THE APPLIED LOADING

In the design of the pavement thickness the civil engineer is not so much concerned with the maximum all-up weight of the aircraft as with the load from the main undercarriages and with the greatest intensity of pressure likely to be applied by a single wheel or group of wheels. This intensity is measured approximately by the tyre pressure. It is true that the walls of the tyre support some of the weight of the aircraft and that intensity of contact pressure can be equated to tyre inflation pressure only with a perfectly flexible tyre. The discrepancy arising from the assumption that inflation pressure is equal to contact pressure is small and is generally neglected. Tyre pressures (and therefore thicknesses of pavement) are increasing. In 1948 the tyre pressures used in 34 well-known civil and military aircraft ranged from 36 lb./in.^{2} to 85 lb./in.^{2}. The I.C.A.O. classification provides for pressures up to 120 lb./in.^{2}. Even higher pressures are in use (*see* Table I), and in the United States some aircraft have a tyre pressure of 200 lb./in.^{2}.

TABLE I

DESIGN CHARACTERISTICS OF FOUR MODERN AIRCRAFT

Aircraft	*All-up Weight (lb.)*	*Main Wheel Arrangement*	*No. of Wheels in Main Undercarriage*	*Tyre Pressure (lb./in.^{2})*	*Estimated Equivalent Single Wheel Load (E.S.W.L.) (lb.)*	*Main Undercarriage Load (lb.)*	*E.S.W.L. as % of Undercarriage Load*	*Radius of Contact Area (E.S.W.L.) (in.)*
A*	105,000	Twin Tandem	4-35 in.	115	23,400	48,780	48	8.1
B	53,000	Twin Side-by-side	2-36 in.	90	14,800	24,700	60	7.2
C†	120,000	Twin Tandem	4-35 in.	140	27,600	57,300	48	8.0
D	37,000	Twin Side-by-side	2-34 in.	60	9,900	16,500	60	7.2

*Comet I
†Comet II

(By permission of the Ministry of Supply)

The second factor which governs the design of pavement thickness is the area of contact of the wheel with the surface. The greater this area, the greater the depth to which significant stresses are carried within the pavement and subgrade. The area is easily determined from the total wheel load and the tyre pressure. The shape of the area of contact also has some bearing on the stresses within the foundation. Although the true contact area is approximately elliptical little error is introduced if it is assumed to be circular or rectangular, assumptions which allow of simpler mathematical calculation of the theoretical stress.

The third important factor influencing the stress within the foundation material is the wheel arrangement of the main undercarriage. If the undercarriage transmits a heavy load to the pavement this load is usually dispersed and the stresses in the pavement reduced by using groups of wheels. Common arrangements are twin wheels side by side, two wheels in tandem, four wheels on a single bogie, or even, as in the Bristol Brabazon Mk. 2, eight tyres on a single bogie.

When calculating the thickness of the pavement, the engineer finds it more convenient to use an equivalent single wheel load (E.S.W.L.) rather than the complex arrangement used in the aircraft. The problem then arises of deciding what alleviation of stress has been achieved by the dispersal of load through two or four wheels. There is no simple solution to the problem of determining an equivalent single wheel load, and for a given aircraft and main undercarriage it can even be said that there are different equivalent single wheel loads for each runway condition. The alleviation of pressure achieved by the use of tandem, twin and twin-tandem arrangements also depends on the spacing of the wheels, on the area of tyre in contact with the running surface, and on the stiffness of the slab. The data for the four modern aircraft described in Table I show an E.S.W.L. of 48 and 60 per cent. of the total undercarriage load, but the limits are much wider than this, especially for four-wheel bogies, and can range from below 30 per cent. to above 65 per cent. The most authoritative statement on this problem is that by Cooper,[11] to which reference should be made for details too complex to be included in this brief review of the problem.

3. MEANS OF SUPPORTING THE APPLIED LOADING

The properties required in the pavement may best be considered in relation to the several layers of which it is composed. The functions of each layer are twofold. Firstly it must be strong enough to resist the shearing and direct stresses imposed by the intensity and spread of the loading. Secondly it must be thick enough to ensure that the layer below is not overstressed.

To-day the pavement consists of surfacing, base, and sub-base as a minimum construction and below this lies the natural or compacted subgrade. The layers of the pavement decrease in strength in the order given, the thickness of each depending on the strength of the layer below.

Of the two types of runway commonly described, the "flexible" pavement is of bituminous materials and is expected to follow differential settlements of the subgrade without cracking. The second, or concrete type is inflexible and cannot adjust itself to a deflected foundation, but is capable—because of its ability to carry shear and tensile stresses—of relieving the subgrade of stress by spreading the applied load over a larger area. A modern development is that of pre-stressed concrete in which high tensile steel wires apply compressive loads to the concrete before it is stressed by the applied loading. A few runways and roads have been constructed in this way, but the method is, as yet, experimental in aerodrome construction. A pre-stressed concrete runway has many of the desirable properties of both flexible and rigid types. It is sufficiently flexible to follow displacements of the subgrade without cracking, and because of its flexibility, and the fact that there is a compressive stress over the whole cross section, can be much thinner than the conventional rigid pavement. The watertightness of the pre-stressed concrete pavement is also a valuable property. Unlike the normal concrete pavement, the pre-stressed concrete slab has few joints and no major cracks and can thus repel surface water and protect the subgrade.

4. METHODS OF FAILURE OF THE SUBGRADE

Failure of a runway to carry its load is made evident by a deterioration of the surface, but this is not always caused by a fault in the surface material. In the majority

of instances the surface failure is due to the collapse of the subgrade. This can happen in two ways. The material may fail to sustain a local intensity of shearing stress and give way on small slip planes under the pavement. Such stability failures can be guarded against by providing an adequate thickness of artificial pavement above the subgrade. The second method of failure has its origin in a volume change due to variation in moisture content or due to repeated loadings. This is most serious in the cohesive soils, although sand foundations have also been known to break up when the underlying soil was drained. The chief object of the various design procedures is to afford protection against these two methods of failure.

5. THE INFLUENCE OF THE MOISTURE CONTENT

The emphasis which McAdam placed on the necessity for waterproofing the "native soil" or "subgrade," as it is now called, and his realisation of the part played by moisture content is of fundamental importance and has more bearing on the failure of runways or perimeter tracks to support their loads than any consideration of the manufacture of the running surfaces.

The strength of a soil to support an applied load and the properties which it displays are dependent on the intergranular contact developed between the particles of the soil. In some soils the grains are pressed together by their own weight only. In others, particularly in clays, the particles also cohere because of the molecular forces brought into play by the minute size of the individual grains. The fundamental truth that the intergranular pressure between particles is largely responsible for the strength of the soil is true for both extreme types.

Most soils in nature, particularly those in the alluvial plains so suited to modern aerodrome construction, are saturated. The interstices between grains or between connected chains of particles are filled with water which can flow through the interstices under the action of gravity or of superimposed pressure.

When the soil is dry, the total load is resisted by the intergranular pressure on which the frictional resistance of the soil and, hence, its strength depends. When static water occurs within the soil, the intergranular pressure is reduced from its value for dry soil by the value of the pore-water pressure. The soil is weakened even by standing water and, if the water is flowing upwards against the direction of gravity, the intergranular pressure is still more reduced and the soil weakened further. Thus, any increase in moisture content of the soil leads to a decrease in its strength, and the aim of the civil engineer is to prevent surface water from entering the foundations of runways and perimeter tracks both by the provision of impervious wearing surfaces and by the removal of surplus surface water as quickly as possible. An approximation to a stable water content ensures that volume changes in the soil are small and that the strength of the subgrade is not reduced.

Quite as important as its effect on the shearing strength of the soil is the effect of moisture content on the volume. As has been mentioned already, abstraction from, or addition to, the moisture content of a saturated soil results in a change in volume. When water is withdrawn by drainage, evaporation, or a steady pressure, the decrease in volume is equal to the volume of the water abstracted. This can have serious consequences during a drought when the soil under the edges of a runway can be much drier than the more effectively protected soil under the centre. The resulting differential settlement causes disintegration even in a flexible pavement, and serious cracking in a rigid pavement. Rain entering through these cracks not only weakens a clay subgrade, but causes the clay to swell and aggravate the weakened condition. If the water table is normally kept low under aerodrome pavements by adequate subsoil drainage, and if surface water is taken off as rapidly as possible—perhaps by longitudinal channels under slots in the runways—danger of volumentric changes is much reduced. The chief function of the drainage system is to decrease the possibility of the weakening of foundations by percolating water and by the changes in volume consequent upon rise and fall of the water table.

It is well to note that for each value of total pressure on a soil there is a unique value of the void ratio (ratio of void to solid volume), provided that the pressure has acted sufficiently long to produce a condition of equilibrium. If the soil is saturated, as usually assumed, then there is a defined equilibrium moisture content for each value of superimposed pressure, and the soil gradually reaches that condition. If then,

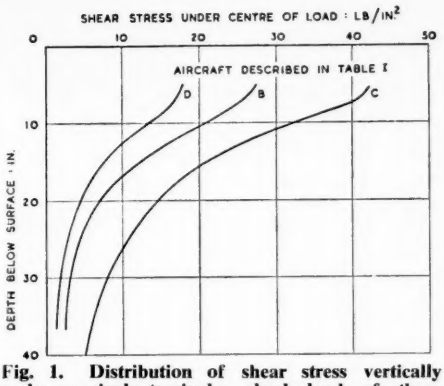

Fig. 1. Distribution of shear stress vertically under equivalent single wheel load of three modern aircraft.

the soil, by reason of exposure to the weather, is at some other moisture content when the pavement is laid, the condition of over- or under-saturation is perpetuated under the slab. Such a condition is unstable and the moisture content gradually changes towards equilibrium. Whatever change takes place results in alteration in volume. It is highly important, therefore, to cover the subgrade with a sealing coat immediately the surface soil is stripped. At Hatfield Aerodrome, the formation was covered by a blinding coat of weak concrete within a few hours of stripping. The effectiveness of this step was considered to be so important that the thickness of three inches of 12:1 concrete was later increased to six inches of 9:1 concrete.

6. PROPERTIES OF THE SOIL

None of the properties of the soil on which calculation of runway strength depends can be defined briefly in exact terms. Even the shearing strength of the soil, which might be considered a fundamental property, varies with the time the normal load is allowed to act and with the rate at which the shearing test is carried out. It is usual, however, to measure the "immediate" shearing strength of the subgrade for a few feet below the surface. The shear box which gives a direct measure of shearing strength, or the tri-axial compression test which gives the shearing strength indirectly, can both be used, and the more recently developed vane tests give *in situ* readings quickly.

A second property whose value is used in the design of pavements, is the rate at which the subgrade deflects under a steady pressure. This "Modulus of Subgrade Reaction" is measured by jacking a circular bearing plate into the soil. The value obtained varies with the size of the loading plate used, and the figure is given as (load/in.²)/in. or pressure developed per inch of deformation.

A final property is even more arbitrary and empirical than the second. A cylindrical plunger, whose flat end has an area of 3 in.², is driven down into a prepared sample of the soil usually for two minutes at 0.05 in./min. The pressure in lb./in.² required to do this is expressed as a percentage of 1,000 lb./in.² which has been found to be the pressure required to effect penetration into an eminently suitable subgrade material. This ratio is the California Bearing Ratio; the higher its value, the more resistant the material to shearing failure.

With these properties of the soil and the results of the calculation of theoretical stresses in the subgrade, the engineer has several methods at his disposal of designing the required thicknesses of runways and hard-standings. These methods do not all give the same results and are by no means free from faults or above criticism. They are, however, the only methods at present available, and can be divided into two procedures in general use. Two other methods not discussed here are that based almost entirely on theory and that relying on the simple classification of the soil without regard to its physical properties.

7. PAVEMENT THICKNESS FROM THE SHEAR STRENGTH OF THE SOIL

The theoretical distribution of shearing stress within a homogeneous, elastic, isotropic and semi-infinite mass loaded at the surface was first defined by Boussinesq in 1885. The vertical distributions of shearing stress directly under a uniformly distributed circular load are shown in Fig. 1 for three of the four aircraft of Table I.

Having decided on the appropriate distribution of shearing stress in the subgrade, the engineer compares these stresses with the shearing strength of the soil. A profile showing the change of shearing strength with depth is drawn from the results of unconfined or tri-axial compression tests. This profile can then be superimposed on the shear stress diagram as is shown in Fig. 2 for Aircraft *A* and *D*. When the shear strength

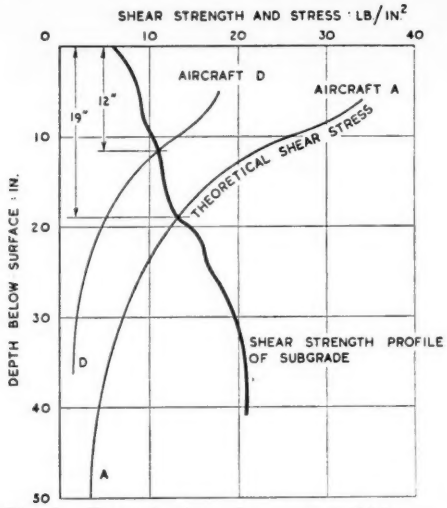

Fig. 2. Determination of pavement thicknesses for aircraft *A* and *D* from the theoretical shear stress distribution.

line is to the left of the shear stress line, a stronger material than the subgrade is required. When the stress line is to the left of the strength line the subgrade is adequate in shear. It thus appears that a pavement thickness of 19 inches is required for Aircraft *A* and of 12 inches for Aircraft *D*. Fig. 2 shows a modification of a method first proposed for clay subgrades by Glossop and Golder[3] and found to agree well with results in practice.

It can be realised that this does not represent the true state of stress throughout the depth of pavement and subgrade, for the material is neither homogeneous nor isotropic. If the upper layers are stiffer (have a higher modulus of elasticity) a greater proportion of the load is resisted by stresses in upper layers, and the subgrade is not so highly stressed. The mathematical work required to determine the stresses in two-layer and three-layer systems is complex, but has been done by Fox[1] and Acum[2] of the Mathematics Division of the National Physical Laboratory; curves can be drawn and used in the determination of the thickness of pavement necessary for a given load.

When this method is applied to the values found from consideration of a two-layer or three-layer system, various assumptions must be made after a study of the possible materials to be used in the foundation. For example, assuming the thickness of the upper slab to be equal to the radius of the circle of contact and its modulus of elasticity to be 10 times that of the subgrade (although in all probability it would be higher) the curves of Fig. 3 are obtained for Aircraft *A* and *D*. By superimposing the shear strength profile of the subgrade, it is found that the proposed upper layer for *D* adequately protects the subgrade from excessive shear stresses, provided that the upper layer is of sufficient strength to carry the stresses imposed within its own depth. For *A*, however, where a higher tyre inflation pressure is in use, a thickness of strong material equal to the radius of the contact area is not sufficient to protect the subgrade, and a further 5 inches of stabilised material must be used above the subgrade. This leads to a consideration of the three-layer system[2] where a similar distribution of stress can be determined. The calculation of this distribution is complex, but Acum and Fox provide tables from which it can be derived. The shear stress in the subgrade under two other superimposed layers is low and decreases rapidly.

8. PAVEMENT THICKNESS BY CALIFORNIA BEARING RATIO

The approach given in Section 7 is logical, although depending on several assumptions

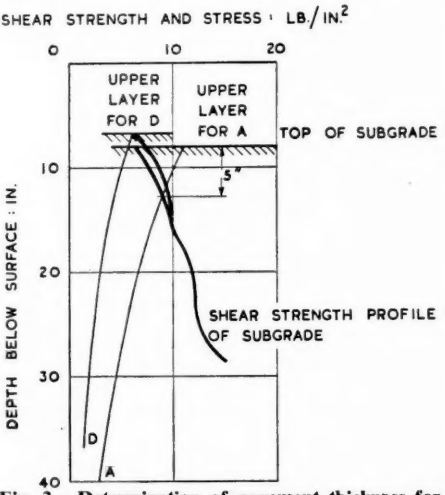

Fig. 3. Determination of pavement thickness for aircraft *A* and *D* assuming an upper layer of 10 times the modulus of elasticity of the subgrade.

and approximations. Another widely used method depends on an empirical study of successful and unsuccessful pavements and places no reliance on theoretical estimation of stresses. The California Bearing Ratio, the determination of which has been described already, is related to the thickness of pavement required merely by empirical curves drawn for given loads from records of failures of construction. Fig. 4 gives these curves as drawn for airports.

If the runway for Aircraft *C* is to consist of a layer of tarmacadam supported by a base of a C.B.R. of 80 per cent. and a sub-base of a C.B.R. of 25 per cent., the various thicknesses required can be read from Fig. 4. For a medium clay MacLean[4] found that at 12 lb./in.^{2} shearing strength (the average on a depth of 2 ft. from Fig. 2) the C.B.R. value for 14½ per cent. moisture content and a dry density of 105 lb./ft.^{3} was about 10 per cent.

Interpolating in Fig. 4 for a load of 28,000 lb.:—

Material	*C.B.R.* (%)	*Depth required above (in.)*
Subgrade	... 10	17
Sub-base ...	... 25	9
Base	... 80	—

It is usually required that at least 6 inches of material with a high C.B.R. should be placed immediately below the running surface to carry the high shearing stresses at that level. Fig. 5 shows the construction proposed with these materials. However, it would probably be more economic and better practice to combine surfacing and base in one slab. The three shear stress lines show that by the modified Glossop and Golder method the total slab thickness would be several inches deeper than is required by the C.B.R. method.

Figure 5 shows how an increase in tyre pressure for the same load results in increased shear stresses. As the tyre pressure for the E.S.W.L. of Aircraft *C* is raised from 100 to 200 lb./in.^{2}, the stress at 6 inches below the running surface changes from 30 to 60 lb./in.^{2}. The C.B.R. method takes no account of such variation in inflation pressure and Fig. 4 is based on tyre pressures normally in use. There is evidence, however, that pressures are increasing rapidly even for the same wheel loading. The inflation pressure for Aircraft *C*, for example, is already 16 per cent. above that recommended for Class I runways. For the upper layers of a pavement the C.B.R. method therefore may show insufficient thickness if tyre pressures have been raised since the curves of Fig. 4 were designed.

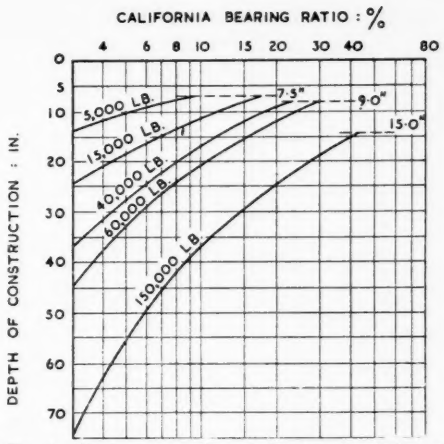

Fig. 4. Design curves for runways under different wheel loads (aprons, hard standings, and so on are somewhat thicker for the same load). *(U.S. Corps of Engineers.)*

9. METHODS OF DESIGN FROM A STUDY OF SOIL DEFORMATION

The two widely used methods of design given in Sections 7 and 8 rely on an index of the strength of the subgrade and of the constituent parts of the pavement. In the first procedure the shear strength measured is an independent property of the material but in the C.B.R. method the strength index is quite arbitrary, is not a fundamental property, and can be used only in the C.B.R. investigation.

Some investigators have considered that excess displacement rather than the failure of strength causes failure of the pavement, and have based their theories on this assumption. Of these methods, Burmister's[5] for flexible pavements, and Westergaard's[6] for concrete slabs are the best known. Both use a value of displacement, Burmister limiting the deformation under the slab to an arbitrary 0.2 in., and Westergaard assuming displacement to be proportional to the load applied. Burmister uses the modulus of elasticity of the soil and Westergaard the modulus of subgrade reaction. These moduli are related by the expression

$$E = 1.18\,ak$$

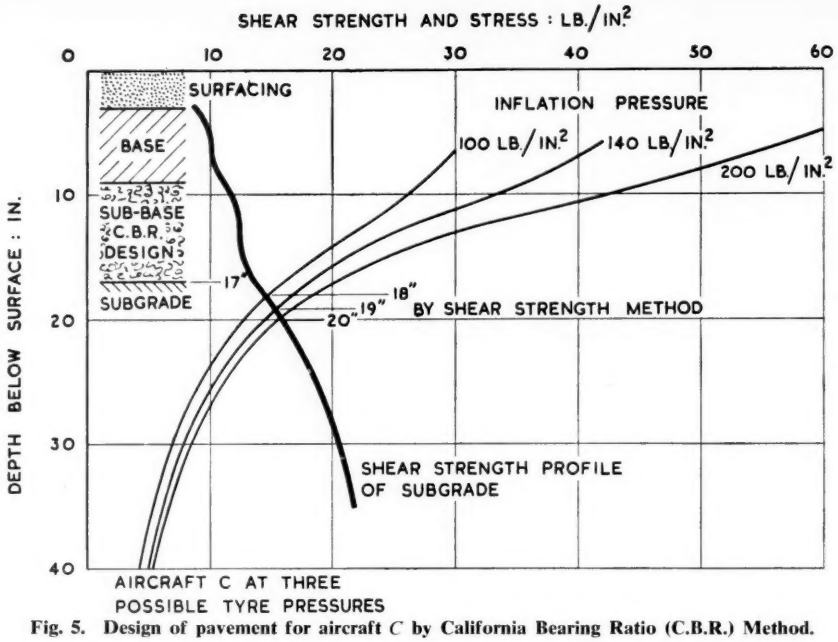

Fig. 5. Design of pavement for aircraft *C* by California Bearing Ratio (C.B.R.) Method.

where

E is the modulus of elasticity (lb./in.²)

a is the radius of the contact area (in.)

and

k is the modulus of subgrade reaction (lb./in.³).

Westergaard's original analyses were for highway loadings but have been modified for runways, and have also been related, by Teller and Sutherland[7], to experimental work.

10. METHODS OF DESIGN USING AN EMPIRICAL INDEX

Two empirical indices are in use. One—the Group Index—relies on the classification of the soil to define the thickness of pavement required. A formula built up from the grading of the soil and its consistency limits gives the value of the Group Index of the subgrade. Empirical curves based on experience give values of the thickness of the subbase. The thicknesses of base and surfacing are also defined, and depend on an estimation of the type of traffic. This method applies to roads rather than runways and takes no account of tyre pressures.

The other index in use is the Runway Loading Index which, contrary to the Group Index, does not include factors referring to the soil, but takes note only of the wheel load (w) and tyre pressure (p). As pointed out by Dykes[8] the Runway Loading Index is proportional to $w^m\ p^{1-m}$ an expression which is constant for equal runway strengths. Rodin's work for British Overseas Airways Corporation, using a deflection theory gave the value of m as 0.50, and Foster's chart[9] (Fig. 6) shows one estimation of how runway strength varies with w and p. The expressions proposed have been either $w^{0.56}\ p^{0.44}$ or $w^{0.50}\ p^{0.50}$, both of which give a measure of the loading effect on the runway.

If w is taken as the load on the wheel group (lb.) and p as the nominal tyre pressure (lb./in.²) then Table II gives the Runway Loading Index for the four aircraft of Table I.

By relating these to a standard classification the type of runway required for each aircraft can readily be chosen.

The bare solution given in Table II probably oversimplifies the problem of determining a criterion of runway strength

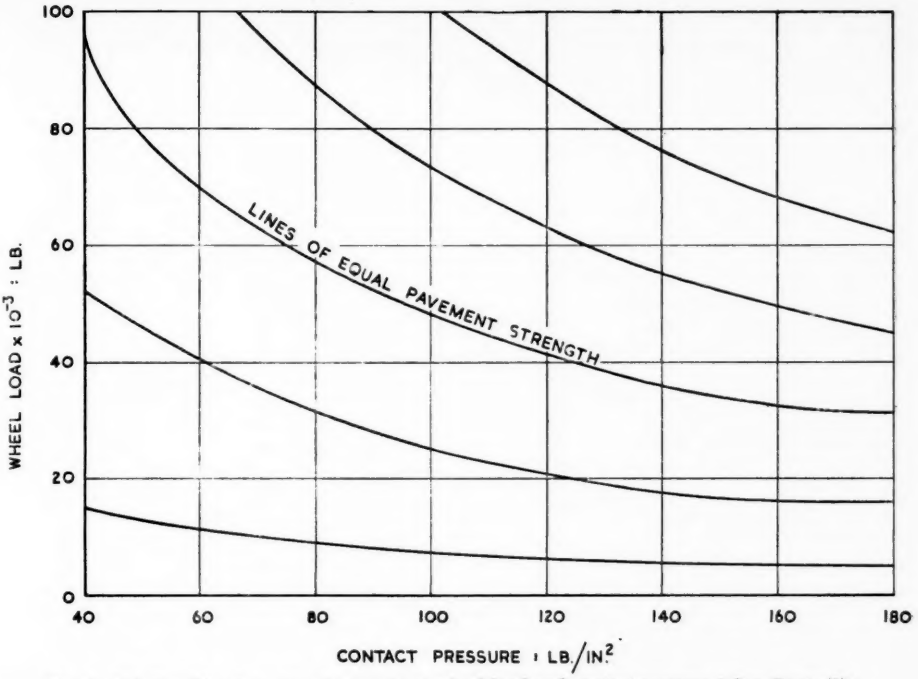

Fig. 6. Relationship of pavement strength to wheel load and contact pressure (after Foster[9]).

for a given aircraft. Corrections must obviously be made to the Runway Loading Index (R.L.I.) to allow for types of undercarriage arrangement. The values of w and p may also vary considerably (even in an individual aircraft) with varying conditions of loading, altitude of airport, temperature and maintenance. The R.L.I., however, does take into account any changes in the tyre pressures normally used, and is an important criterion of runway strength.

Table III shows how a third column added to the I.C.A.O. classification indicates how the basic R.L.I. value varies from Class 1 to Class 7.

Examining the value of $\sqrt{(wp)}$ for the four modern aircraft of Table I gives Table III.

TABLE II
RUNWAY LOADING INDEX

Aircraft	*A*	*B*	*C*	*D*
Load on wheel group (lb.)	48,780	24,700	57,300	16,500
Tyre pressure (lb./in.²)	115	90	140	60
R.L.I. $\sqrt{wp}$ (lb./in.)	2,370	1,490	2,830	990

11. CRITICAL SUMMARY OF METHODS OF RUNWAY DESIGN

The factors influencing the strength of a runway are numerous, and no one method of design takes direct account of them all. The factor most commonly used as a guide to the thickness of the pavement is the strength of the subgrade, but only the deformation methods take direct account of its elasticity. These methods too (except for the latest development of the Shear Strength Method) are the only ones to include direct reference to the elastic properties of the pavement layers above the subgrade. The California Bearing Ratio method takes indirect note of most of the factors

TABLE III
I.C.A.O. STRENGTH CLASSIFICATION

Class	*w (lb.)*	*p (lb./in.²)*	*$\sqrt{(wp)}$ (lb./in.)*
1	100,000	120	3,460
2	75,000	100	2,740
3	60,000	100	2,450
4	45,000	100	2,120
5	30,000	85	1,600
6	15,000	70	1,030
7	5,000	35	420

influencing strength, but is the only one to include directly the influence of possible softening of the subgrade. To some, the soaking of the C.B.R. test specimen before test to simulate the rising of the water table to the surface, is too severe, and results in an unnecessarily conservative design. The tyre pressure is taken into account directly by the Shear Strength Method and by the deformation methods, but only indirectly by the C.B.R. method. The C.B.R. includes allowance for repeated loading, an important recommendation not mentioned directly by the other methods discussed.

When a method seeks to simplify the problem or when it concentrates on one part of the pavement to the exclusion of the rest, numerous important factors are omitted from consideration. The simple shear strength method, logical and neat as it may appear to be, takes no note of the frequency of loading, the elasticity of the subgrade, or the properties of the surfacing, although if the recent work on two- and three-layer systems is used, this last factor is accounted for. Westergaard's method, although not seeking to simplify the problem, deals only with the concrete slab, and although the slab may be properly stressed there is no guarantee that the subgrade will not be overstressed. Other methods completely neglect the stiffness of the surfacing and its ability to spread load over a wide area. The Index methods ignore one side of the problem and produce an index which deals either with the loading or with the subgrade but not with both. The link between aircraft loading and runway strength must still be empirical and depend on the teachings of experience.

12. CONCLUSIONS

The summary of the methods of runway design given in this paper shows that the matter has not reached finality. The most used method for rigid pavements (Westergaard's) does not take enough account of the type of subgrade, and the C.B.R. method —the most reliable one for flexible runways —derives its results from a study of wheel load only, assuming that tyre pressures remain as they were when the empirical tests were made. There is evidence, however, that tyre pressures are tending to be higher in proportion to wheel loads and, as shown in Fig. 5, higher tyre pressures for the same load increase the shearing stress in the first few feet below the surface. To the civil engineer this tendency to higher pressures is of significance, for it is the intensity of loading rather than its total value which governs his runway strengths. If the aircraft constructor considers that intensity of contact pressure must be increased, the opposing tendency towards the development of multi-wheel undercarriages helps to prevent the runway thicknesses required on poor alluvial soils becoming uneconomic. It would be failing to learn the lessons of history if the aircraft were forced to conform to the state of runway design of today or tomorrow, but it is no longer sound to assume that the civil engineer can build an economic pavement for any type of aircraft. With the weight of undercarriages becoming equal to half the payload,[10] the diverse claims of multiple-wheels, tyre pressures, and types of pavement, present one combined problem. Perhaps in the future, the solution will require a complete change in the methods of launching and retrieving aircraft.

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Note on Ultimate Strength of Webs in Shear

by

R. TATHAM, B.A., A.F.R.Ae.S.

INTRODUCTION

An investigation into the preparation of Data Sheets based on the work of Kuhn and Griffith[1] at the N.A.C.A., revealed that it might be possible to present non-dimensional curves for the ultimate shear strength of aluminium alloy webs in incomplete diagonal tension, in a form similar to that of Structures Data Sheet 02.03.13, which are independent of material specifications. The values of "basic allowable shear stress" are founded on flat plate details from early experimental work and on estimated values for fully developed diagonal tension. Later work by Ross Levin[2] provided further test results extending the range of diagonal tension developed, and the application of these to thick webs has been confirmed.

NOTATION

A_s = cross sectional area of stiffener (in.^{2})
b = plate width between stiffeners (in.)
t = sheet thickness (in.)
k = diagonal tension factor
q = nominal shear stress (lb./in.^{2})
q_a = allowable shear stress (lb./in.^{2})
q_b = buckling shear stress (lb./in.^{2})
f_u = ultimate tensile stress for the material (lb./in.^{2})
Suffix 24S-T applies to 24S-T specification material
Suffix 75S-T applies to 75S-T specification material

EXPERIMENTAL CURVES

The N.A.C.A. curves are drawn for two specific materials, 24 S-T and 75 S-T, and for each material two curves are given. The upper curve corresponds to webs which are not allowed to buckle at the edges of rivet holes, a condition obtained either by clamping the plate between two heavy flanges or by using a heavy washer under the rivet head. The lower curve corresponds to webs which have a flange on only one side and in which the rivet head is allowed to bear directly on the plate, offering no restraint against buckling at the edge of the rivet hole; tests by Ross Levin and Nelson[3] indicate that in this case the strength is about 11 per cent. less than when the webs are not allowed to buckle at the edges of rivet holes. The results, as finally presented, have been reduced to correspond to the specified ultimate tensile stresses of 62,000 lb./in.^{2} for 24S-T and 72,000 lb./in.^{2} for 75S-T. The ultimate shear stress is plotted against the "diagonal tension factor" k, which specifies the degree to which diagonal tension is developed. For flat plates, k is defined by Kuhn and Peterson[4] by the equation

$$k = \tanh\left[0.5 \log_{10} \frac{q}{q_b}\right] \quad . \quad (1)$$

where q is the nominal shear stress, and q_b the buckling shear stress.

REDUCTION TO NON-DIMENSIONAL FORM AND COMPARISON OF MATERIALS

An evaluation of the ratio

$$\left(\frac{q_a}{f_u}\right)_{24S-T} \Big/ \left(\frac{q_a}{f_u}\right)_{75S-T}$$

where q_a is the allowable shear stress taken from the curves given by Ross Levin in N.A.C.A. T.N. 1756 and f_u is the ultimate tensile stress of the material, for various values of k leads to an approximately constant figure. Taking the mean value of this ratio as 0.925, the maximum variations from this mean value are of the order of $+1.08$ per cent. and -1.3 per cent. It is suggested, therefore, that a single curve could be drawn for 24S-T, and that values for 75S-T may be derived from this curve using the relation

$$\left(\frac{q_a}{f_u}\right)_{75S-T} = \left(\frac{q_a}{f_u}\right)_{24S-T} \times \frac{1}{0.925}. \quad (2)$$

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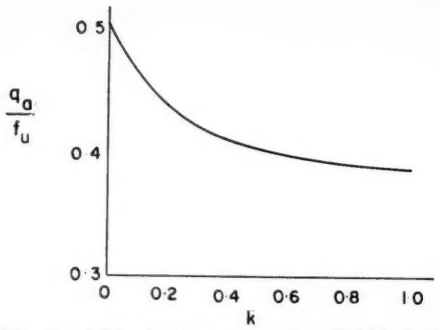

Fig. 1. Ultimate shear stress for 24S-T sheet (from N.A.C.A. Tech. Note No. 1756). Values of q_a/f_u for 75S-T are 1/0·925 × values from this curve. For web with flange on one side only and with rivet head bearing directly on web, use 0·89 × value of q_a/f_u from this curve.

Furthermore, only the upper of the two experimental curves referred to need be drawn, since the lower curve was derived from the upper by reducing the allowable shear stress by 11 per cent., *i.e.* the lower curve may be obtained by multiplying the ordinates of the upper curve by 0.89. The non-dimensional curve for 24S-T is shown in Fig. 1, together with the information necessary for conversion to 75S-T, using the relation (2).

In the opinion of Ross Levin, the difference in the ratio q_a/f_u for the two materials is due primarily to the presence of rivet holes and the stress concentration arising at these holes. At failure it is evident from work done by Stowell[5] that the stress concentration factors for the two materials may be different, and tests included in the report of Ross Levin and Nelson show that this is so.

In order to incorporate other materials further experimental work is required but, in the absence of such experimental evidence it is suggested that a linear variation of q_a/f_u with f_u may be assumed, of the form

$$\frac{q_a}{f_u} = \left(\frac{q_a}{f_u}\right)_{24S-T} \{1 + C(f_u - f_{u24S-T})\} \qquad (3)$$

where C is a constant.

Inserting the values for 24S-T and 75S-T yields

$$\frac{q_a}{f_u} = \left(\frac{q_a}{f_u}\right)_{24S-T} \left\{1 + 0.00825\left(\frac{f_u}{1{,}000} - 62\right)\right\} \qquad (4)$$

That this expression gives reasonable agreement for 75S-T is shown in Fig. 2, where the 75S-T curve from Ross Levin's work is compared with equation (4). It is suggested that, over the range of aluminium alloys normally used, no serious errors would be incurred by using equation (4) together with the basic curve for 24S-T.

It should be noted that in order to give agreement with the manner in which the experimental results were reduced by Ross Levin to correspond to specific values of f_u, the specified value of f_u should be used on the right hand side of (4). Having then determined the value of the ratio q_a/f_u, the actual value of f_u may now be used to determine the actual allowable shear stress, since the reduction formula used was

$$q_{spec} = q_{actual} \times \frac{f_{spec}}{f_{actual}}$$

where q_{spec} = "reduced" allowable shear stress.

COMPARISON WITH R.Ae.S. DATA SHEET 02.03.13

Using equation (1) the allowable shear curves for 24S-T and 75S-T are shown in Fig. 3, compared with the curves for failure as given in the Royal Aeronautical Society's Structures Data Sheet 02.03.13. A curve for $A_s/bt = 0$ has been added, extrapolated from the 02.03.13 curves, since the N.A.C.A. results are based almost entirely on tests on long unstiffened plates. The data sheet curves are theoretical and take no account of

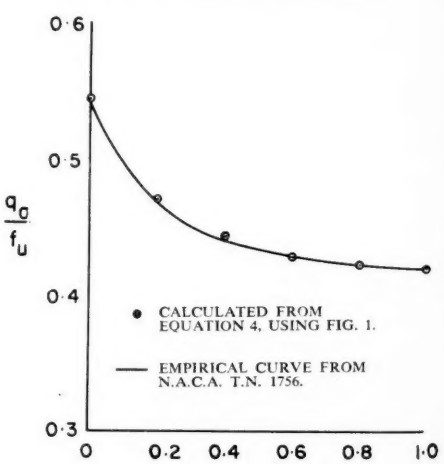

Fig. 2. Ultimate shear strength of 75S-T sheet.

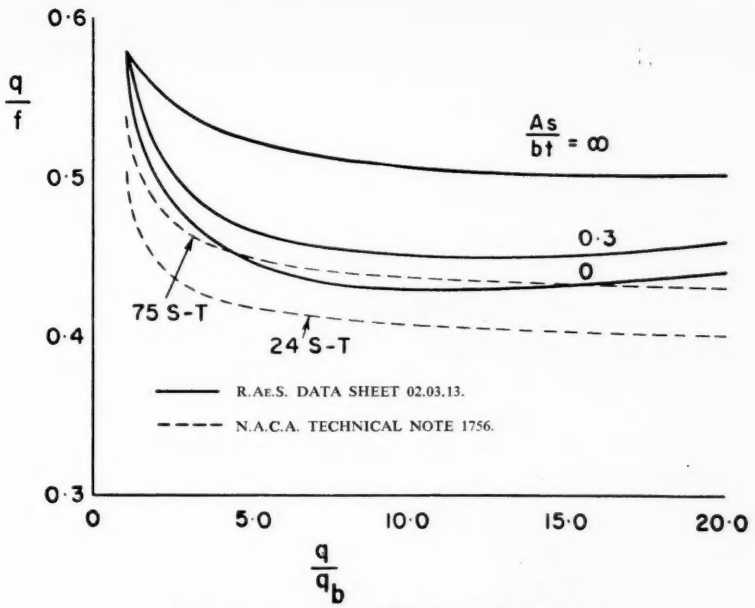

Fig. 3. Shear stress at failure of aluminium alloy sheet.

variation in material properties, or of stress concentration at rivet holes, but do make allowance for the degree of stiffening present.

Although there is quite good agreement between the curves for 75S-T and the curves for $A_s/bt=0$ extrapolated from 02.03.13, the curve for 24S-T falls some 10 per cent. below the 02.03.13 curve. While it may be considered that this 10 per cent. variation is acceptable, it is suggested that further experimental work is desirable to investigate the variation of ultimate shear strength with material characteristics.

In view of the fact that proof conditions might be critical, experimental investigations to determine the shear stress to cause permanent deformation would also be welcomed.

CONCLUSIONS

The experimental evidence available in N.A.C.A. Technical Notes suggests that the curves of R.Ae.S. Data Sheet 02.03.13 giving the allowable shear stress for failure may be too high for some aluminium alloys. Pending further experimental work it is suggested that equation (4) combined with the basic curve for 24S-T shown in Fig. 1 may serve as a guide on which to base design data. It is apparent from the work of Stowell, however, that q_s/f_u will vary, not only with f_u, but also with the shape of the stress-strain diagram and hence with the ratio of proof stress to ultimate stress. Nevertheless, equation (4) should give values of sufficient accuracy for initial design purposes.

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On the Present and Potential Efficiency of Structural Plastics

by

J. E. GORDON

SUMMARY

Structural plastics are based on fibres which are about three times as strong and as stiff for their weight as the metals in an aircraft structure. However, two thirds of the weight of existing plastic structures consists of resins which contribute little to the overall strength and stiffness. Moreover, the fibres which constitute the remaining third of the weight are inefficiently disposed with regard to the loads which they have to carry. Existing materials, therefore, are inefficient compared with metals. In spite of this, plastic structures have been made with a performance at least equivalent to that of metal ones. It therefore follows that the efficiency of these plastic structures, as structures, is high. The scope for improving the materials is great and, if the structural efficiency can be maintained, corresponding savings of weight should result.

The limit of improvement of existing materials such as Durestos has nearly been reached but, by employing the fibres in parallel bands, suitably crossed, a material affording combinations of shear and tensile properties about twice as efficient as those of Durestos should be attainable, resulting in structures of about half the present weight. This is probably about the limit of improvement using existing fibres and methods.

Short of employing better fibres, if they exist or can be made, the best hope for still further improvement seems to lie in the use of thin plates of alumina as a reinforcement. Such a material should be about twice as efficient again as the best asbestos-based material and about four times as good as Durestos, but the practical difficulties of development would be great.

1. INTRODUCTION

This paper attempts to make a critical survey of existing plastic materials, and in particular of Durestos (a felted asbestos material used in many Royal Aircraft Establishment experiments[14]), to review the principles which govern their manufacture and mechanical properties and to enquire whether the limit of improvement of existing materials has been reached. It also attempts to decide upon what lines it is profitable to try to develop new materials and what magnitude of improvement may be expected, together with the effect that such improvements might have upon the weights of aircraft structures. To achieve this aim it is necessary to establish, at least tentatively, criteria by which structural plastics may be compared both among themselves and with metals.

A difficulty with plastics is that they do not lend themselves to simple concepts and to simple comparisons. Engineers commonly ask "What is the tensile strength of such and such a plastic?" At the back of the questioner's mind is perhaps the idea that, if one could answer "So many tons per square inch," he would then be able to create some kind of mental picture of the substance and be able to compare it with more familiar materials.

A single property such as tensile strength may indeed serve as a rough criterion of the character of metals and of certain other isotropic materials, but it can have

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no more relevance as a standard of comparison for structural plastics than for reinforced concrete, for neither of these materials are simple substances but are rather artificial structures. Within certain limits both can be designed to have any desired properties in any required direction.

The necessity for criteria for heterogeneous materials is twofold. The aircraft engineer needs them in order to assess the weight and efficiency of a proposed plastic structure, while the plastic research worker is in need of guidance as to how to improve his materials.

How can a comparison be made of materials which differ so widely from metals and whose density, aeolotropy and other properties are variable? The answer can only be, by measuring their fitness for use in an aircraft structure. It is necessary to examine the nature of these materials and from this to determine, not what may be the maximum value of any single property, but what combinations of properties are attainable in relation to the structural requirements of an aircraft.

For the present purpose all such ancillary substances as sandwich cores and adhesives are left aside and only primary stress-carrying materials are considered; moreover, the nature and design of plastic structures are of interest only in so far as they bear upon the properties desirable in plastic materials.

NOTATION

P_1	stress along most highly stressed axis (usually spanwise in a wing, axially in a fuselage, and so on), taken as 0° or x-axis for two-dimensional analysis, z-axis for three-dimensional cases
P_2	stress at right angles to P_1 in plane of shell structure, y-axis in two-dimensional cases (or 90°) (usually chordwise in a wing, and so on), x-axis in three-dimensional cases
P_3	stress normal to P_1 and P_2
e_1, e_2, e_3	corresponding strains
E_1, E_2, E_3	corresponding Young's moduli (specific)
G	shear modulus (specific), usually parallel to P_1 and P_2
θ	angle a fibre makes with axis of P_1
ψ	angle between plane containing fibre and P_1 and $z0y$ plane
$f(\theta)$ and $f(\theta, \psi)$	fibre distribution functions
n and m	indices of functions of θ in distribution functions
E_f	specific fibre Young's modulus
k	ratio of modulus of resin-fibre continuum to axial fibre modulus
χ	*see* Section 6.2
σ	Poisson's ratio, usually of continuum
α	material efficiency criterion
F	ratio of relevant specific fibre property to that of metals
η_r	resin content efficiency
η_0	orientation efficiency
E_1' and G'	true or observed values of E_1 and G
β	structural efficiency criterion
p	proportion of fibres in given partial orientation

2. THE PRINCIPLES OF STRUCTURAL PLASTICS

2.1. FIBRES AND RESIN

All the structural plastics which have been developed up to the present have been made by gluing together various kinds of fibres with synthetic resins. Later in this paper it is suggested both that the resin should play a more important part than that of an adhesive and also, that structural plastics should be made from non-metallic particles other than fibres; nevertheless, in considering existing materials, attention may be confined to fibres and, as a first approximation, it may be assumed that the mechanical properties of these materials depend entirely upon the nature and arrangement of the constituent fibres and the resin may be treated simply as a glue.

The density, strength and Young's moduli of a number of fibres, with some metals and resins for comparison, have been collected from several sources and are given in Table I. Since this paper is concerned with structures of minimum weight, the various materials should be compared by means of their "specific" mechanical properties, that is to say by the actual properties divided by the specific gravity. These specific properties are given in the table.

From Table I, it will be seen that the most promising fibres are glass, asbestos, and the various forms of natural cellulose, and in fact, these are the only fibres from which a serious attempt has been made to prepare structural plastics.

Good asbestos has about three times the specific strength and the specific stiffness of the best metals which would be used in a structure. Dry flax is almost as good. Glass has six or seven times the specific strength of metals but its specific stiffness is only slightly higher than metals.

Cellulose is much the most widely used fibre for commercial reinforced plastics but its sensitivity to moisture has led to its being rejected for aircraft structures both in this country and in America.

TABLE I

PROPERTIES OF CERTAIN FIBRES IN COMPARISON WITH METALS AND RESINS

Material	*Specific gravity (approx.)*	*Ultimate tensile strength lb./in.²*		*Young's Modulus $E \times 10^{-6}$ lb./in.²*	
		Actual	*Specific*	*Actual*	*Specific*
CELLULOSE					
Flax	1.5	51,000-157,000[2]	34,000-105,000	12.5-15.6[1]	8.3-10.4
Hemp (wet)	—	—	—	5.0[1]	3.3
(air dry)	1.5	130,000[2]	87,000	8.25[1]	5.5
(desiccated)	—	—	—	11.0[1]	7.3
(dried under tension)	—	—	—	12.3[1]	8.2
Ramie (wet)	—	—	—	2.7[1]	1.8
(air dry)	1.5	110,000[2]	73,000	7.4[1]	4.9
(desiccated)	—	—	—	8.5[1]	5.7
(dried under tension)	—	—	—	13.1[1]	8.7
(mercerised under tension)	—	—	—	11.6[1]	7.7
Wood fibre (Kraft paper) (approx.)	1.5	130,000[3]	87,000	10.5[3]	7.0
Cotton (average)	1.5	51,000[2]	34,000	—	—
Ordinary viscose	1.5	12,000[2]	—	1.2[1]	0.8
Lilienfeld viscose (highly orientated)	1.45	—	—	3.5[1]	2.3
Cellophane	1.5	3,700[5]	2,500	0.9[1]	0.6
Cellulose acetate film	1.26	5,000-8,000[4]	4,000-6,400	0.4[1]	0.3
Cellulose nitrate film	1.45	7,000[4]	4,800	0.4[1]	0.3
OTHER ORGANIC FIBRES					
Nylon	1.07	72,000[6]	67,000	0.7[6]	0.7
Wool	1.3	23,000[2]	17,700	0.4[6]	0.3
Silk	1.3	64,000[2]	49,000	1.0[6]	0.8
ASBESTOS					
High grade chrysotile fibres	2.4	216,000[3]	90,000	26.5[3]	11.0
GLASS					
Quartz fibre (lab. sample)	2.65	3,500,000[9]	1,320,000	10.0[7]	3.8
Commercial glass fibre	2.4	500,000[4]	210,000	10.8[8]	4.2
APPROX. FIGURES FOR METALS					
Steel piano wire	7.8	350,000	45,000	30.0	3.85
Aircraft structural steel (85 ton)	7.8	190,000	24,000	30.0	3.85
Duralumin	2.8	60,000-90,000	21,000-32,000	10.5	3.75
Magnesium alloy	1.8	43,000	24,000	6.5	3.61
APPROX. FIGS. FOR SOME RESINS					
Methyl methacrylate	1.2	7,000[4]	6,000	0.4[2]	0.3
Phenol formaldehyde	1.3	5,000-9,000[4]	4,000-7,000	0.3-0.6[4]	0.2-0.5
Phenol furfuraldehyde	1.3	7,500[4]	6,000	0.7-0.9[4]	0.5-0.7
Moulded nylon	1.1	9,000[4]	8,000	0.3[4]	0.3
Polystyrene	1.05	3,000-8,500[4]	3,000-8,000	0.2-0.5[4]	0.2-0.5
Polyvinyl formal (Formvar)	1.2	2,500-12,000[4]	2,000-10,000	0.3[4]	0.3

In America, the very great strength of glass fibre has caused attention to be confined almost exclusively to this material, although its low stiffness must be a serious handicap. In aircraft structures the stiffness of the material frequently has as much effect upon the structure weight as the strength. This is for two reasons:—

(*i*) Shell structures tend to fail under compression or shear by buckling before the ultimate strength of the material is reached.

(*ii*) The stiffness requirements which are necessary to prevent flutter or aileron reversal are exacting.

Since the prospect of improving the stiffness of glass fibres is not promising[8], research has been concentrated at the R.A.E. for several years almost entirely upon asbestos, which provides an excellent combination of strength and stiffness.

With the arrangements of fibres which have so far been used the choice of resin has little effect upon the mechanical properties of reinforced plastics, so long as the resin does not soften or otherwise deteriorate under the working conditions. It was found in the "Pykrete" experiments during the Second World War[10] that an excellent "plastic" could be made from wood fibres and ice.

The relatively low softening temperatures of most thermoplastic resins exclude them from aircraft structures while, if the softening temperature could be increased sufficiently, the moulding temperature would be inconveniently high.

By far the most widely used resins are those of the phenol formaldehyde type because (*i*) being thermosetting they are relatively little affected by the temperatures encountered in service, (*ii*) they are cheap compared with most other resins and, an important practical point, (*iii*) they have a so-called "B stage" in which the uncured resin is dry and clean to handle and has a long working life; this last property greatly simplifies the assembly of large mouldings. Until recently these resins were considered as being suitable only for high moulding pressures, which meant that it was impracticable to make large aircraft mouldings from them. The development of the R.A.E. atmospheric pressure moulding process has eliminated this objection[14]. Work at the R.A.E. on resins for structural plastics has been concentrated upon the improvement of resins of this type.

Working with glass fibres, the Americans have used the polyester or "contact resins" almost exclusively. These can be set at very low pressures because no water is evolved during the cure. These resins have no "B stage" so that they are sticky and have a short working life after the catalyst is added. This objection is being overcome by the "injection process" in which the fibres are assembled in the mould before impregnation and, after the pressure is applied, the resin is injected, being so catalysed and accelerated as to set rapidly at room temperature. This seems a promising process for glass fibres but it probably cannot be used with asbestos which seems to be impermeable to resins under these conditions. The "contact resins" are more expensive than the phenolics and seem likely to remain so.

Since the resin is so much weaker than the reinforcement it is clear that reinforcing particles of granular or spherical shape, however strong, would be of little use because the material could break in the resin before the reinforcement was carrying any appreciable stress. This is the reason for using fibres which provide a large surface area along which the weak component must break before failure can take place.

However, the problem is not simply one of providing an area for adhesion such that the product of this area and the shear strength of the resin is equivalent to the tensile strength of the fibre, because the stress distribution along the resin-fibre interface is complicated, as is known by analogy from glued and bolted joints. Fortunately, in practice it is found that the adhesion is such that the full strength of the fibre is usually realised.

2.2. Resin content

When parallel fibres are added to a resin which is then hardened, the strength and stiffness of the resin is increased in the direction of the fibres in proportion to the addition of fibres, according to a simple mixture law (Fig. 1). The strength and

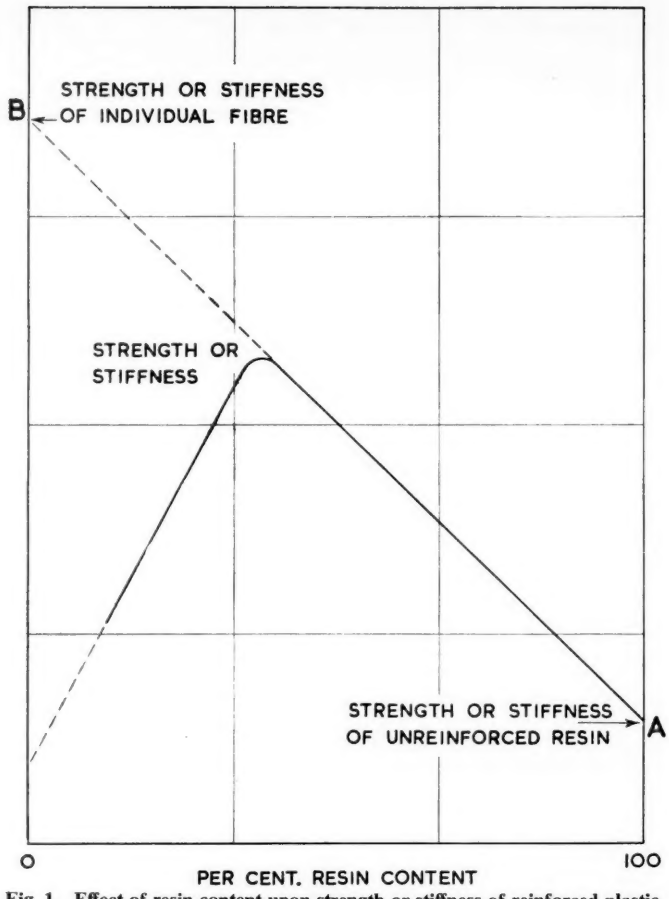

Fig. 1. Effect of resin content upon strength or stiffness of reinforced plastic (parallel fibres).

stiffness continue to increase in a linear manner as fibres are added until a critical resin content is reached. The properties then fall rapidly until, when there is no resin, the material has merely the strength of the unimpregnated material, which is derived from the friction between the fibres.

The peak in the curve corresponds to the minimum amount of resin which will just glue the fibres together efficiently and this is, of course, the optimum resin content. Pepper[11] has shown that with cellulose fibres, this resin content corresponds very closely to the "voids" or the volume of empty space between the fibres which exists under the conditions of pressing and curing; the reason for this will be seen later. As might be expected, the peak is higher up the line *AB* (Fig. 1) the higher the moulding pressure and the better the packing of the fibres.

With inorganic reinforcements such as asbestos and glass the peak in the curve does not appear to correspond to the "voids" and so a somewhat lower resin content can be used with a corresponding benefit. Another benefit comes from using inorganic reinforcement; this is because the density of such fibres is considerably higher than cellulose and since the criterion of minimum resin content is by volume, the actual content by weight may be substantially lower.

With high pressing pressures, resin contents as low as 20 per cent. may be used and the benefit of small changes in resin content is small. When using the low moulding pressures, which are convenient for making large components, the packing of the fibres is necessarily much less close and anything which tends to reduce the minimum resin content is very beneficial.

For simplicity, this argument has been given for the case of parallel fibres but a precisely similar argument applies to other arrangements of fibres, except that the "target" at which the line AB is aiming is not the strength and stiffness of a single fibre but the theoretical strength and stiffness of a mat of fibres with the given orientation.

2.3. Dependence of cellulose reinforcement on moisture

The strength and stiffness of a completely dry cellulose fibre is about three times that of one saturated with water. The moisture content of cellulose quickly reaches an equilibrium with the humidity of the surrounding air and thus the properties of cellulose are not only considerably lower than they might be, but vary with the ambient humidity.

With natural cellulosic materials, such as wood, little can be done about this except to slow down the changes to some extent by painting the material.

With cellulose-reinforced plastics the conditions are rather different. Cellulose swells when it gets wet and shrinks as it dries; the moisture equilibrium for a given ambient humidity is affected by the state of stress in the fibre.

It has been shown by the author, in an unpublished paper, that the moisture content, and therefore the swelling, strength and stiffness can be controlled to some extent in this way. If the fibres are carefully dried immediately before the impregnated material is pressed and cured they will remain, after curing, in a state of stress and thus will be permanently drier than if they were unrestrained. In this way a properly made material reinforced with cellulose is markedly better in all respects than the cellulose would be in a natural state. However, the restraint of the response of the fibre to moisture is only a partial one and most of the well-known disabilities of cellulose as an engineering material remain, although to a less extent. Moreover, cellulose-reinforced materials require careful control of the manufacturing conditions, particularly at low moulding pressures; this control is difficult to achieve, especially when moulding large objects.

Referring to Section 2.2, it will be seen that the fall in properties which occurs when the resin fails to fill the voids completely is probably due to a lack of restraint by the resin on the fibre, since the restraint seems to be a physical one.

With inorganic fibres which are only very slightly hygroscopic these considerations can be neglected.

2.4. Toughness and brittleness

All the reasons why a material is tough or brittle are not fully understood but it is clear that, if a material is to avoid the effects of the very high concentrations of stress which must occur at cracks and holes if it truly obeys Hooke's law, then some kind of shear flow must occur locally without markedly weakening the material. In metals shear flow is provided by the fact that most metallic crystals can deform along certain planes without becoming weaker.

In non-metallic materials no comparable mechanism exists upon a molecular or atomic scale. It is true that some linear polymers, such as polyethylene, can deform by a somewhat similar sliding action but this property seems necessarily to be associated with thermoplasticity and creep. Rubbers and similar materials are, in the engineering sense, extremely brittle but, since their Young's modulus is so low, they usually avoid the consequences; nevertheless, a crack will run in a stretched rubber sheet as readily as in glass.

This being so, it is necessary to arrange for some sort of shear flow upon a macroscopic scale. This is usually done by controlling to some extent the adhesion

of the resin to the fibre. The shear strength of asbestos is so low and the adhesion of resins to glass usually so poor, that the necessary toughness is achieved with these materials, as it were, accidentally.

With cellulose more care is needed. If the resin impregnates the fibre intimately the moisture resistance is improved but the material becomes extremely brittle. In structural plastics, therefore, care is taken to impregnate in such a way that the character of the adhesion is more that of a physical embedding.

2.5. Fibre orientation

This subject, which is vital to the proper understanding of reinforced plastics, gives an almost unlimited scope to the mathematician. It is necessarily treated fairly briefly here so that it is impracticable to review the experimental evidence in detail.

It is convenient to refer all orientation calculations to an ideal material with zero resin content. The calculated results can then be modified as desired in accordance with Section 2.2.

All the author's calculations upon fibre orientation have been based upon the mathematics of H. L. Cox[16]. Since Cox's paper has not yet been published* some of his calculations have been reproduced with his permission in order to make what follows comprehensible.

2.5.1. *The plane mat with random fibre orientation*

Cox considers an element in a plane mat of fibres, which are supposed to be infinitely thin and to be rigidly joined where they cross each other. The element is a square of unit side and is subject to stresses P_1 and P_2 parallel to its sides which cause strains e_1 and e_2 respectively.

Consider a fibre crossing the element so as to make an angle θ with the P_1-direction. Its unstrained length within the element is $\sec\theta$. When the element is strained by amounts e_1 and e_2 the strain in the fibre will be $(e_1\cos^2\theta+e_2\sin^2\theta)$.

If the effective fibre modulus be E_f, say, then the load carried by the fibre will be $E_f(e_1\cos^2\theta+e_2\sin^2\theta)$.

If the lateral separation between the fibres is assumed to be statistically uniform, then the number of fibres at angle θ crossing the base line of the element will be proportional to $\cos\theta$. If the fibres are distributed in angle according to any distribution function $f(\theta)$ then the number of fibres crossing the base line at angle θ will be $\cos\theta\, f(\theta)$.

The total load in all these fibres (at angle θ) is therefore

$$E_f(e_1\cos^2\theta+e_2\sin^2\theta)\cos\theta\, f(\theta).$$

Hence the total stress P_1 must be

$$\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} E_f(e_1\cos^2\theta+e_2\sin^2\theta)\cos^2\theta\, f(\theta)\,d\theta\,.$$

This expression is dependent on the total number of fibres in the element, which is unknown; therefore P may be considered as a specific stress by dividing by the number of fibres:—

$$P_1=\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{E_f(e_1\cos^2\theta+e_2\sin^2\theta)\cos^2\theta\, f(\theta)\,d\theta}{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} f(\theta)\,d\theta}\,.$$

*The paper by H. L. Cox has since been published; it is given as Reference 16.—Ed.

Similarly

$$P_2 = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{E_f(e_1 \cos^2\theta + e_2 \sin^2\theta)\sin^2\theta\, f(\theta)\, d\theta}{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} f(\theta)\, d\theta}.$$

Cox evaluates these equations for the randomly distributed case when $f(\theta)=1$ (*i.e.* fibres uniformly distributed in all directions in a plane). This yields:—

$$P_1 = \tfrac{3}{8} E_f(e_1 + \tfrac{1}{3} e_2) \text{ and } P_2 = \tfrac{3}{8} E_f(e_2 + \tfrac{1}{3} e_1).$$

Then if E_1, E_2 be the Young's moduli in directions P_1 and P_2, and writing $P_2=0$ and $P_1=0$ in turn:—

$$E_1 = E_2 = \frac{P_1}{e_1} = \tfrac{1}{3} E_f.$$

Similarly the strength is $\frac{1}{3}$ of the fibre strength. Also Poisson's ratio is $\frac{1}{3}$ and the shear modulus, $G = E_f/8$.

These results are in good agreement with experiment.

2.5.2. *The plane mat with non-random orientation*

2.5.2.1. *Uni-axial normal distributions*

Making use of Cox's equations which have just been derived, the author investigated the properties of some plane non-random orientations[12]. Consider first the cases where the fibres are neither random nor parallel but something between the two; this is a common type of orientation which occurs both in most papers and in Durestos felts.

It would seem reasonable to treat this, and all analogous cases, by means of a polar Gaussian distribution function, but such a function cannot be integrated. Fortunately trigonometric distribution functions of the type to $f(\theta)=\cos^n\theta$ will serve as quite close approximations to the Gaussian distribution (at least for the higher values of n) and are convenient to manipulate. The author has calibrated n in terms of an approximate standard deviation of the fibre scatter in degrees[12].

Using $f(\theta)=\cos^n\theta$, Cox's equations yield

$$P_1 = E_f \frac{n+1}{(n+2)(n+4)} \{ e_1(n+3) + e_2 \}$$

and

$$P_2 = E_f \frac{1}{(n+2)(n+4)} \{ e_1(n+1) + 3e_2 \}.$$

Whence

$$E_1 = \frac{P_1}{e_1} = E_f \times \tfrac{3}{4} \frac{n+1}{n+2}.$$

This expression gives reasonable values for E_1 for low values of n, *i.e.* for orientations which are not markedly parallel. However, in the case where the fibres approach a truly parallel state, when $n \to \infty$ $E_1 \to \frac{3}{4} E_f$, an apparently anomalous result. This effect, which is of some importance, is considered again in Section 2.5.5.

2.5.2.2. *Bi-axial normal distributions*

Certain other simple orientations can be treated by modifications of this technique, for example the case, which is analogous to plywood, when two sets of

laminae with more or less highly orientated fibres which cross each other at right angles can be examined by means of the function

$$f(\theta)=\cos^n\theta+b\sin^m\theta.$$

For high values of m and n the equations yield such moduli as would be expected and there are no anomalous results comparable to that just noticed, but when a is nearly equal to b, and m and n have low or moderate values, the moduli do not differ sensibly from the random case, a result which is experimentally useful, since it enables substantially random specimens to be prepared from oriented laminae.

2.5.3. *The solid mat with random orientation*

The general equations for the solid mat have been derived by Cox in a manner very similar to that for the two-dimensional case. He has employed the following system of polar co-ordinates. It is supposed that three stresses P_1, P_2 and P_3 act parallel to the z-, x- and y-axes respectively, and cause strains e_1, e_2 and e_3. A fibre is considered as making an angle θ with the z-axis while the plane containing the fibre and the z-axis makes an angle ψ with the $z0y$ plane.

Hence by reasoning analogous to Section 2.5.1:—

$$P_1=\frac{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} E_f(e_1\cos^2\theta+e_2\sin^2\theta\cos^2\psi+e_3\sin^2\theta\sin^2\psi)\cos^2\theta\, f(\theta,\psi)\,d\theta\,d\psi}{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} f(\theta,\psi)\,d\theta\,d\psi}$$

$$P_2=\frac{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} E_f(e_1\cos^2\theta+e_2\sin^2\theta\cos^2\psi+e_3\sin^2\theta\sin^2\psi)\sin^2\theta\cos^2 f(\theta,\psi)\,d\theta\,d\psi}{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} f(\theta,\psi)\,d\theta\,d\psi}$$

$$P_3=\frac{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} E_f(e_1\cos^2\theta+e_2\sin^2\theta\cos^2\psi+e_3\sin^2\theta\sin^2\psi\sin^2\theta\sin^2\psi\, f(\theta,\psi)\,d\theta\,d\psi}{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} f(\theta,\psi)\,d\theta\,d\psi}.$$

For three-dimensional randomness $f(\theta,\psi)=\sin\theta$. So that

$$P_1=\frac{E_f}{5}(e_1+\tfrac{1}{3}e_2+\tfrac{1}{3}e_3),\qquad P_2=\frac{E_f}{5}(\tfrac{1}{3}e_1+e_2+\tfrac{1}{3}e_3)$$

and

$$P_3=\frac{E_f}{5}(\tfrac{1}{3}e_1+\tfrac{1}{3}e_2+e_3).$$

Whence Young's modulus $=E_f/6$, Poisson's ratio $=\frac{1}{4}$ and the shear modulus $=E_f/15$ in all directions.

Three-dimensional randomness is difficult to achieve experimentally because the fibres tend to be flattened into the plane of consolidation during moulding, but there is no reason to suppose that these results are in error.

2.5.4. *The solid mat with non-random orientation*

2.5.4.1. *The approach to plane random orientation*

Cox has examined the case where the solid random mat approaches the plane random mat and finds that the limiting case differs from that deduced in Section 2.5.1, another anomalous result.

2.5.4.2. *Uni-axial normal distribution*

A case examined by the author is that where the fibres, from being random in three dimensions, approach parallelness in a manner defined by the solid of revolution created by rotating the polar Gaussian curve about the z-axis which is also its mean.

These arrangements of fibres may be approximated by using the distribution function

$$f(\theta, \psi) = \sin\theta \cos^n \theta.$$

Integrating Cox's three-dimensional equations gives

$$P_1 = \frac{n+1}{n+5} E_f \left\{ e_1 + \frac{e_2}{n+3} + \frac{e_3}{n+3} \right\},$$

$$P_2 = \frac{n+1}{(n+3)(n+5)} E_f \left\{ e_1 + e_2 \frac{3}{n+1} + e_3 \frac{1}{n+1} \right\},$$

$$P_3 = \frac{n+1}{(n+3)(n+5)} E_f \left\{ e_1 + e_2 \frac{1}{n+1} + e_3 \frac{3}{n+1} \right\}.$$

Whence

$$E_1 = \frac{P_1}{e_1} = \tfrac{1}{2} \frac{n+1}{n+3} E_f.$$

This reduces correctly to $E_f/6$ for the random case when $n=0$ but, as the fibres approach parallelness $n \longrightarrow \infty$ when $e_1 \longrightarrow E_f/2$, which is again apparently anomalous.

2.5.5. *The resin continuum*

It is suggested that the anomalies of Cox's equations indicate not that these equations are in any way positively in error, but rather that they do not by themselves fully describe the behaviour of the materials concerned. The position is:—

(*a*) The anomalies do not appear to proceed from any mathematical artifact, such as a lack of realism in the distribution functions, since similar results can be obtained by using a variety of distribution functions.

(*b*) Anomalous values are only obtained when one or more of the other moduli becomes vanishingly small and the appropriate Poisson's ratio correspondingly large. No such effects are observed, for example, for the "crossed" fibre distributions of Section 2.5.2 although they occur with analogous "uncrossed" distributions. In other words the anomalous effects all proceed from excessive secondary strains.

(*c*) It was for some time supposed that these anomalies were of a purely theoretical nature. Working with asbestos, some experimental results have recently been obtained which can only be explained on the basis of the calculation in 2.5.4.2. In other words some sensibly parallel arrangements of asbestos fibres were found to possess about half the expected Young's modulus.

It will be seen that anomalous moduli are caused by a lack of transverse fibres resulting in excessive secondary strains. In other words the structure which has been considered is a "deficient" one. The fact that such results are rarely encountered in practice with fibre orientations, which at least approximate to those considered, shows that lateral support is usually provided in a manner extraneous to Cox's equations. The discrepancy is caused by the assumption that the fibres are infinitely thin and therefore do not interfere with each other laterally.

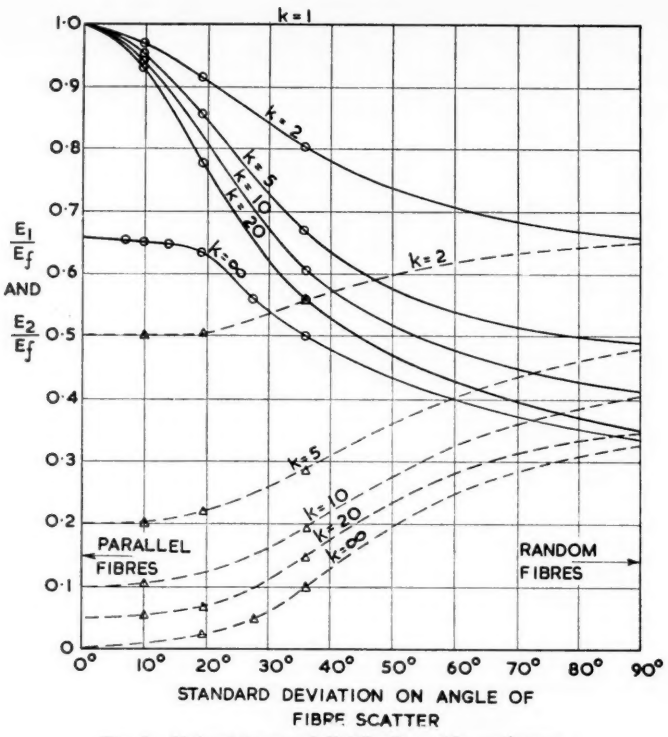

Fig. 2. Uni-axial normal distribution with continuum. Effect of k and of fibre orientation upon E_1 and E_2.

——————— **Longitudinal (E_1)**
— — — — — **Transverse (E_2)**

In fact the fibres and resin usually form a more or less continuous medium giving some lateral support to all the fibres. The actual mechanism is clearly complex and aeolotropic. It has been suggested[12] that it should be replaced mathematically by a continuous isotropic medium in which infinitely thin fibres are embedded like wires in a jelly. This medium may be considered as having a Young's modulus of E_f/k.*

If the properties of the orientations considered are now recalculated, using this concept, it is found that the moduli of the more random orientations are little affected, while the anomalous cases disappear and are replaced by the values which would be expected from common sense considerations.

Within wide limits the value of k has comparatively little effect on the moduli. Very high values (over 100) are sufficient to eliminate the anomalous cases, whereas the true values of k may be in the region of 10 to 20 (*see* Table I). Some effects of k on the case considered in Section 2.5.2.1 are plotted in Fig. 2.

It will be seen that although the resin plays an essential part, other than that of an adhesive, at least when extreme orientations are employed, for the orientations which have been considered, which comprise all those now in use, an improvement

*In all the calculations which follow, where a continuum is employed, the fibre modulus has been reduced to $E_f(k-1)/k$ otherwise, in a parallel fibre material for example, the stiffness of the continuum would be added to that of the fibres along the fibre axis, which is clearly untrue.

in the stiffness of the resin would have little effect on the moduli of the material and indeed such stiffness as the resin now possesses is not being efficiently exploited.

As for the anomalous experimental results referred to, it is easy to split asbestos indefinitely into thinner and thinner fibres along the planes of crystal cleavage. If the fibres are harshly treated before impregnation they may be full of sub-microscopic parallel cracks which may not be accessible to the resin on impregnation. If this occurs, a state of affairs will exist within the fibres which corresponds very closely to that described in 2.5.4.2.

3. EFFICIENCY CRITERIA

The weight of a structure is determined by the product of two factors:—

(*i*) The efficiency of the material in resisting loads. That is to say it is determined by some function of the various mechanical properties of the material independently of its shape. It is proposed to derive a criterion α which is a rough measure of this efficiency, relative to aircraft structural metals.

(*ii*) The efficiency of the structure as a structure, that is, an intrinsic efficiency of shape independent of the mechanical properties of the material. This is a function both of ingenuity of design and of the manufacturing potentialities of the material. As it is difficult to establish any absolute standard of efficiency in engineering design, it is proposed to use a criterion β which is a multiple of the weight of an arbitrarily chosen metal structure of good design.

Hence the weight of a plastic structure will be $1/(\alpha\beta)$ times the weight of a comparable orthodox metal structure, which is relatively easy to assess from the large body of existing data.

α and β are now derived.

3.1. THE MATERIAL EFFICIENCY CRITERION

Let $$\alpha=\frac{\alpha_p}{\alpha_m}$$

where α_p = criterion for plastics

α_m = criterion for metals.

α_m is discussed further in Section 4.1.

α_p may be divided into three components such that

$$\alpha_p=F\eta_r\eta_0.$$

Here F represents the relevant specific fibre property (strength or stiffness) in relation to metals.

η_r is that fraction of the theoretical strength of the fibre mat at zero resin content which is actually realised. That is to say, it allows for the diluent effect of the resin and will normally be proportional to the fibre content of the material.

η_0 is the efficiency with which the fibres are orientated.

F and η_r present no difficulties, but η_0 must be considered in some detail.

The great majority of aircraft structures are concerned with thin shells so that, locally, the material may be considered two-dimensionally. Also, in nearly all aircraft structures (wings, fuselages, control surfaces, propeller blades, and so on) there are likely to be two important stress systems. The first is due to bending along the length of the component (*e.g.* spanwise in a wing). This causes, in the main, tension and compression in the bottom and top surfaces respectively and shear in the webs and leading edge of, for example, a wing. The chordwise stress component is usually small. The second main stress system is due to torsion and causes tensile and compressive stresses at $\pm 45°$ to the lengthwise axis of the component.

The general requirement therefore is for strength and stiffness at $-45°$, $0°$ and $45°$ to a given axis. Stresses at $90°$ are often relatively small. The ratio of shear to spanwise tension or compression is, however, very variable, not only between components but from place to place in the same component.

In a structure in which the fibres were ideally orientated the tension, compression and shear requirements would just be met at each point. It is proposed to call a structure with such an orientation "eutropic."

The search for eutropy is therefore one for the best combinations of shear with uni-axial properties. In an elaborate unpublished investigation[13] Cox examined the properties of a two-dimensional fibre mat with a distribution function capable of representing any fibre orientation. He found that, neglecting the resin continuum, the optimum combinations of E_1 and G were defined by,

$$E_1 + 4G = E_f.$$

Since the aeolotropy of strength and stiffness is found by experience to be closely proportional[12], a similar relation will presumably hold for the strength case. Thus η_0 may be defined as

$$\eta_0 = \frac{E_1 + 4G}{E_f},$$

where, at zero resin content, E_1 and G are the calculated or "ideal" values.

At first sight such a criterion might seem relevant only to fibrous materials, since for continuous materials like metals the relation between E and G is

$$G = \frac{E}{2(1+\sigma)}.$$

The "cost" of shear properties in metals is much lower than in plastics. It might therefore be supposed that this criterion was unduly favourable to metal. On reflection, however, it will be seen that the relation $E_1 + 4G = E_f$ applies to any material which is used in a manner analogous to fibres (*e.g.* a metal lattice structure). The use of metals to make lattice structures wastes the transverse properties of the material, for these are only effectively employed by using the metals in sheets. With fibrous materials, however, there is (neglecting the continuum) no theoretical difference between the efficiency of a lattice and that of a shell structure. This ability to exploit the isotropic nature of metals in plate structures is, therefore, a virtue of continuous materials which must be counted against fibrous ones in assessing efficiencies. If E_1' and G' be the real or observed values, then

$$\eta_r \eta_0 = \frac{E_1' + 4G'}{E_f},$$

so that $\alpha_p = (E_1' + 4G')/E_{\text{metals}}$ for stiffness, and similarly for strength.

This leads to the difficulty of having two criteria, one for strength and the other for stiffness and, in assessing the weight of a structure, there is no easy way of telling which criterion is likely to be critical. There does not seem to be any universally applicable solution.

A limited solution may be achieved along the following lines. The specific strengths and also the specific stiffnesses of the common aircraft structural metals, steel, duralumin and magnesium alloy, are substantially equal. The specific strengths and stiffnesses of good cellulose and asbestos fibres are also roughly equal and are in each case nearly enough three times those for the metals quoted. Therefore, for general comparative purposes, F for asbestos and cellulose may be taken as three times F for metals, both for strength and stiffness, without substantial error.

Another difficulty about the suggested criterion is that, although it assesses the combination of E_1 and G for the particular case under investigation, it takes no account of the versatility of the material, that is to say of the range of values of E_1 and G which are attainable; it will readily be understood that two materials having equal values for α may differ widely in their suitability for a particular structure if the particular combination of E_1 and G present in one material is less suited to the application than that in another. For example, a parallel fibre material such as Gordon Aerolite will give a comparatively high value for α and yet be less useful for applications involving shear loads than an isotropic material with a lower value of α.

This means that credit should be given in some form for variability of aeolotropy, yet this seems impracticable from a study of the material alone, since any reliable assessment of this property also involves the nature of the structure.

This being so, it is proposed to include any effects arising out of variation of aeolotropy in the structural efficiency criterion β. This limitation should be borne in mind when considering values for different materials yet it is suggested that, however imperfect a criterion α may be, it does represent some advance on the use of single properties as a method of assessment.

It will be recognised that α is to some extent an arbitrary criterion for, although the relation

$$E_t = E_1 + 4G$$

accurately represents the relative cost in fibres of shear and tensile properties, it is tacitly assumed that shear on the one hand and tension and compression on the other are of equal importance as weight-causing factors. For a wing in bending, for example, possibly two thirds of the material will be subject mainly to tension and compression and perhaps the remaining third mainly to shear. For the torsional stiffness case however, virtually the whole of the material will be subject to shear. If torsional stiffness and bending strength made equally severe demands, then shear would be about twice as important as tension and compression. However, the relative severity of the torsional stiffness and bending strength requirements will vary for different structures and, on the whole, it seems best to leave the criterion in the form which assigns equal importance to both sets of properties.

Such considerations may shift the relative responsibility for structure weight between α and β but, whatever the proportions of these two criteria, similar conclusions will result since the weight which is of interest is the product of the two.

3.2. THE STRUCTURAL EFFICIENCY CRITERION β

This criterion covers, in effect, all the factors which have been left out of account in assessing α; it therefore includes all those empirical qualities which are included in the term "design" and it is necessarily of an approximate nature and can only be taken as a rough guide.

To estimate β, it is necessary to know α and also the weights of equivalent metal and plastic structures which are relevant to the particular type of structure.

Thus $$\beta = \frac{\alpha_m W_m}{\alpha_p W_p},$$

where W_m = weight of metal structure
W_p = weight of equivalent plastic structure
α_m = material efficiency criterion for metals
α_p = material efficiency criterion for plastics.

Note that $\alpha = \frac{\alpha_p}{\alpha_m}$

4. THE EFFICIENCY OF EXISTING PLASTICS

4.1. THE EFFICIENCY OF METALS

As a start α_m may be established as a standard of comparison. For the common structural metals on a specific basis:—

$$E = 3.75 \times 10^6 \text{ lb./in.}^2 \qquad G = 1.44 \times 10^6 \text{ lb./in.}^2,$$

so that $\eta_0 \eta_r = E_1' + 4G' = 2.54$ (by analogy with α_p),

and so if $F = 1.0$, then $\alpha_m = 2.54$.

4.2. THEORETICAL η_0 FOR VARIOUS FIBRE ORIENTATIONS

4.2.1. *Three-dimensionally random orientations*

Neglecting the resin continuum, which has in any case a small effect:—

$$E_1 = \frac{E_t}{6} \text{ and } G = \frac{E_t}{15} \text{ (see Section 2.5.3),}$$

so that $$\eta_0 = \frac{13}{30} \simeq 0.433.$$

4.2.2. *Two-dimensionally random mat*

Again neglecting the resin continuum:—

$$E_1=\frac{E_f}{3} \text{ and } G=\frac{E_f}{8},$$

so that

$$\eta_0=\frac{5}{6}\simeq 0.833.$$

4.2.3. *Uni-axial normal distributions*

As in Section 2.5.2.1

$$E_1=\tfrac{2}{3}\frac{n+1}{n+2}E_f.$$

Moreover Cox[13] calculates that for this orientation

$$G=\frac{(n+1)E_f}{(n+2)(n+4)} \text{ (plotted in Fig. 3).}$$

Whence

$$\eta_0=\tfrac{2}{3}\frac{(n+1)(n+10)}{(n+2)(n+4)}.$$

This expression has a maximum value of unity when $n=2$, which represents a slightly more highly oriented state than that which is usually achieved in paper or felt base materials such as Durestos. Nevertheless it may be concluded that, by this standard, the orientation of such materials is efficient, but difficult to vary.

4.2.4. *Uni-axial normal distributions with continuum*

Values of η_0 for values of k from 2 to ∞ are given in Fig. 4. For the usual values of k (10 to 20) values of η_0 are in the region of 1.1 for optimum fibre orientation.

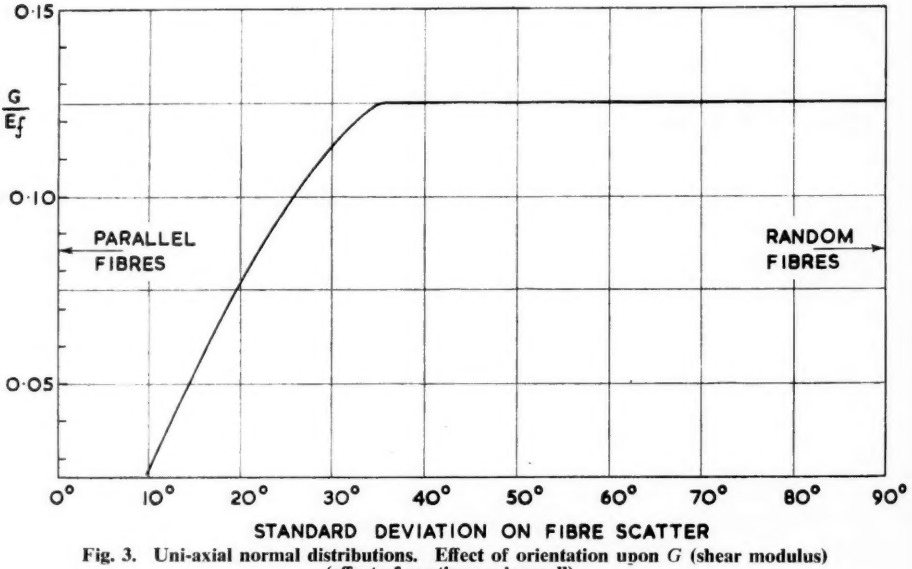

Fig. 3. Uni-axial normal distributions. Effect of orientation upon G (shear modulus) (effect of continuum is small).

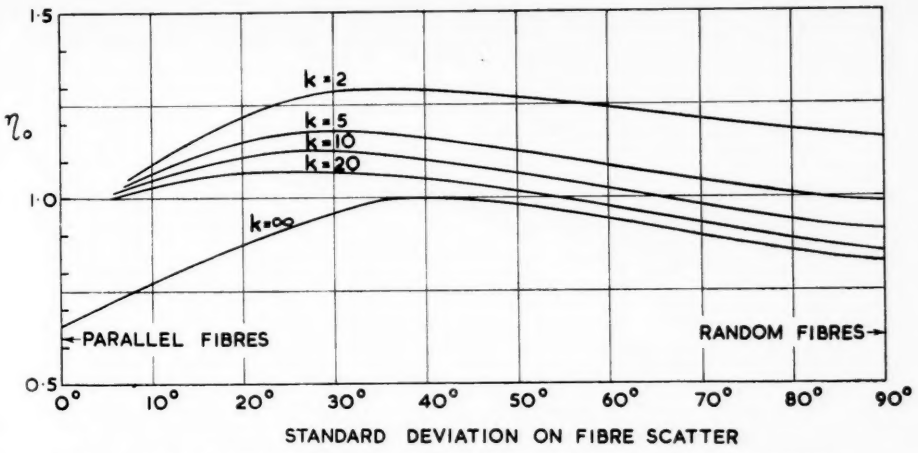

Fig. 4. Uni-axial normal distributions with continuum. Effect of stiffness of continuum = (E_f/R) upon orientation efficiency $\eta_0 = (E_1 + 4G/E_f)$ with various orientations.

4.2.5. *Arrangements of parallel bands of fibres*

For a parallel band of fibres $E_1 = E_f$ and for two equal sets of such bands crossed at $\pm 45°$, $G = E_f/4$.

It is therefore clear that an arrangement with p fibres at $-45°$, q fibres at $0°$ and p fibres at $+45°$ will give $\eta_0 = 1$ for all values of p and q. Moreover, it can be shown that the transverse values obtainable are equal to those which can be obtained with any other orientation.

The advantage of this orientation is that the full range of values of E_1 and G are readily obtainable, so that although η_0 cannot exceed unity the greater versatility should be reflected in increased values of β.

It will be seen from inspection that such an orientation does not benefit greatly by the properties of the resin continuum.

As a matter of interest, the comparable orientation, which has equal numbers of fibres disposed in three sets of parallel bands mutually at 120°, is easily shown to be isotropic in a plane and equal in all respects to the plane random case, a result which is experimentally useful.

4.2.6. *Summary of theoretical results*

It is interesting to translate, as far as possible, the foregoing values of η_0 into actual material efficiencies. Taking $F = 3$ the following values are obtained for $F\eta_0$, which is the maximum theoretical efficiency attainable at zero resin content.

		$F\eta_0$	*Percentage of value for metals*
1.	Metals	2.54	100
2.	Three-dimensionally random fibres	1.30	51
3.	Two-dimensionally random fibres	2.60	102
4.	Uni-axial normal distributions	2.60-3.00	102-118
5.	Three sets of parallel bands (all cases)	3.00	118

In present practice with vacuum moulding resin contents of not less than 50 per cent. have usually to be accepted; neglecting the resin continuum, it may be expected that about the following values may be achieved for α.

	α_p	$\alpha = \frac{\alpha_p}{\alpha_m}$
1. Metals	2.54 (α_m)	1.00
2. Three-dimensionally random fibres	0.65	0.255
3. Two-dimensionally random fibres	1.30	0.51
4. Uni-axial normal distribution	1.30-1.50	0.51-0.59
5. Three sets of parallel bands (all cases)	1.50	0.59

These results made no allowance for the effect of the resin continuum. It is clear that in Cases 2, 3 and 5 the effect will be small. In Case 4 the effect is of the order of 10 per cent.

In general, therefore, for all these orientations the effect will be relatively small so that efficiencies in excess of about 65 per cent. of that of metals are unlikely to be obtained.

4.3. THE EFFICIENCY OF SOME ACTUAL MATERIALS

The two materials which have chiefly been used for structural experiments at R.A.E. are Durestos and Gordon Aerolite. Their resin contents and orientations are known approximately and so α can be predicted as follows:—

	η_0	η_r	$\frac{F}{3.0}$	α_p	$\alpha = \frac{\alpha_p}{\alpha_m}$
Durestos	1.0	0.46	3.0	1.38	0.54
Gordon Aerolite	1.0	0.60	3.0	1.8	0.71

Comparing this prediction with the known performance of the materials, and taking stiffness first, from the actual measured specific values of E_1' and G':—

	E_1'	G'	α_p	$\alpha = \frac{\alpha_p}{\alpha_m}$	$\frac{\text{Actual } \alpha}{\text{Predicted } \alpha}$
Durestos					
Mean values	2.0	0.55	1.12	0.44	0.81
Best laboratory values	2.4	0.60	1.28	0.50	0.93
Gordon Aerolite					
Mean values	5.0	0.23	1.58	0.62	0.88

The calculations from strength values are more uncertain because of the greater variability of strength compared with stiffness. However, taking as the standard of comparison a metal with a specific ultimate tensile strength of 24,000 lb./in.^{2} (*i.e.* an 85 ton steel, a 30 ton aluminium alloy or a 19 ton magnesium) and assuming a shear strength for the metal of three quarters of this value, gives the following results:—

	Specific Ultimate Tensile Strength (*lb./in.*^{2})	*Specific Ultimate Shear Strength* (*lb./in.*^{2})	α_p	$\alpha = \frac{\alpha_p}{\alpha_m}$
Metals	24,000	18,000	3.24	1.0
Durestos				
1949 values	15,700	8,500	2.07	0.64
Gordon Aerolite	38,000	2,400	1.90	0.59

With Durestos the strength figure is higher than the predicted value while the stiffness figure is lower. It will be remembered, however, that an approximate arbitrary value for F was assumed equal to 3.0. In fact the true value of F for asbestos lies a little below 3.0 for stiffness and is somewhat higher than 3.0 for strength. When the correct values are used the agreement with the predicted value is very close (both values being in the region of $\alpha = 0.52$). The convenience of using $F = 3.0$ is so great that it seems worth putting up with the approximation.

With Gordon Aerolite the results are complicated by the effects of moisture on the cellulose fibres. The values given are those usually observed at normal room

humidities (50-60 per cent.). With carefully dried material the predicted values would be achieved.

It may be concluded that, although these materials behave in the calculated manner, the efficiencies which they achieve are only about half those of the common structural metals.

5. THE EFFICIENCY OF EXISTING PLASTIC STRUCTURES

Since so few real plastic structures have been built and tested it is difficult to get reliable weight comparisons. The R.A.E. Mark I Spiteful wing, in its final form, weighed about 96 per cent. of the equivalent metal structure[14]. The Mark II version of the same wing weighs about 85 per cent. of its metal equivalent. Subsequent experience with a number of more advanced structures has indicated that where Durestos structures have been designed and where comparisons are available there has frequently been some saving of weight. American workers have usually claimed a substantial weight reduction. On the other hand, the design of structures in plastic is usually only undertaken where there is a fair prospect of saving weight or at least of not incurring a weight increase. There would certainly be many cases in which a Durestos structure would be heavier than a metal one. Generalising, therefore, it might perhaps be claimed that the weights of Durestos and metal structures are, on average, about equal.

For Durestos $\beta = 0.52$ may be taken as being about the mean realised value. It follows therefore that the structural efficiency criterion

$$\beta = \frac{1.0\,\alpha_m}{\alpha_p} = 1.92 \times \beta_{metals}.$$

In other words, present-day plastics judged purely as materials are only about half as efficient as metals but plastic structures, judged purely as structures, are about twice as efficient as metal ones. At present the two factors so balance each other that the weights of plastic and metal structures are about the same.

The factors which contribute to the high efficiency of plastic structures are the low density of plastics with associated freedom from instability problems, the aeolotropy of plastics, the practicability of almost unlimited thickness variation to suit local requirements, the freedom from joints and the general simplicity of the resulting structures.

In an orthodox metal structure the booms and stringers, which comprise a considerable part of the weight, do not contribute to the torsional stiffness while, at least in the older structures, the skin, which is efficient in shear, is only partly effective in compression. With the thick, stable shells which are a feature of plastic structures spar booms and stringers can generally be eliminated and the whole of the skin material can be made to work effectively in both shear and compression. Any detailed discussion of plastic structures is outside the scope of this paper, which is concerned only with plastic materials.

6. ON POSSIBLE IMPROVEMENTS

6.1. General Review

Since the efficiency of plastic structures is so high, if materials could be achieved which were as good, or nearly as good, as metals, a revolutionary reduction in the weight of aircraft structures might be expected. Such improvement might be looked for:—

(*a*) *By improving the adhesion of the resin to the fibre.* In many cases this will merely make the material more brittle.

(*b*) *By improving the mechanical properties of the resin.* If the resin is to make a serious direct contribution to the strength and stiffness of the material then its properties would have to be increased several times. The possibility of making improvements of this order is not to be dismissed but there does not seem to be

any immediate prospect of them. Smaller improvements could be used, however, to make the fibres themselves work more efficiently; this is considered later.

(*c*) *By using a stronger and stiffer fibre.* The specific E of diamond is about 20×10^6 lb./in.^{2}, which is about twice that of the fibres now in use. That of alumina is about $17\text{-}18 \times 10^6$ lb./in.^{2} There seems, therefore, to be a considerable scope for improving the fibre properties (although these are already very good compared with metals) and it may be well worth making a survey of the properties of suitable crystals.

(*d*) *By reducing the resin content.* The present resin content of Durestos is about 54 per cent. so that η_r is poor. If a substantial reduction could be achieved it would be very beneficial; this may be one of the most promising ways of improving these materials.

(*e*) *By improved orientation.* The limits of improvement by orientation, neglecting the effect of the resin continuum, have been discussed and, as has been seen, they are reached when $\eta_0 = 1.0$, which is achieved, or nearly so, with present orientation. The possibilities of orientations which deliberately exploit the continuum are considered in Section 6.2.

(*f*) *By changing the shape of the fibre.* In a thread-like fibre only the longitudinal properties are utilised, neglecting for the moment the continuum. If the "fibre" had the form of a substantially isotropic plate then its properties in every direction could be used. This is discussed in Section 6.3.

(*g*) *By improved moulding technique.* The detailed technique used when moulding affects the finished material to an appreciable extent, but there is reason to believe (*see* Section 4.3) that the limits of improvement with orthodox Durestos felts are being approached.

6.2. Orientations exploiting the continuum

6.2.1. *The χ-orientation*

Although the author noticed the effect of the resin continuum[12] upon the anomalous moduli implicit in Cox's equations some years ago, it did not then occur to him deliberately to exploit the effect to make use of orientations which would be useless without it. As has been pointed out, with most common orientations, the effect of the properties of the continuum is small and even in the anomalous cases a continuum with a stiffness lower than that which normally exists would suffice. It follows that the stiffness of the continuum is, in a large measure, wasted.

The first orientation in which the fibres deliberately form a deficient structure which will be investigated is that in which equal numbers of fibres form acute angles $\pm\theta$ with the axis of symmetry after the fashion of the letter χ (*i.e.* parallel bands of fibres crossing at angle 2θ), so that it is proposed to call such an arrangement a χ-orientation.

Without the continuum, treating the problem two-dimensionally:—

$$P_1 = E_f \{ e_1 \cos^4\theta + e_2 \sin^2\theta \cos^2\theta \}$$

and

$$P_2 = E_f \{ e_1 \sin^2\theta \cos^2\theta + e_2 \sin^4\theta \} .$$

Introducing a continuum with Young's modulus $= E_f/k$ and Poisson's ratio $= \sigma$,

$$\frac{P_1 k}{E_f} = e_1 \{ (k-1)\cos^4\theta + 1 \} + e_2 \{ (k-1)\sin^2\theta\cos^2\theta - \sigma \}$$

and

$$\frac{P_2 k}{E_f} = e_1 \{ (k-1)\sin^2\theta\cos^2\theta - \sigma \} + e_2 \{ (k-1)\sin^4\theta + 1 \} .$$

Whence

$$E_1 = \frac{P_1}{e_1} = \frac{E_f}{k} \left\{ (k-1)\cos^4\theta + 1 - \frac{((k-1)\sin^2\theta\cos^2\theta - \sigma)^2}{(k-1)\sin^4\theta + 1} \right\} .$$

Similarly

$$G = \frac{E_f}{k} \left\{ (k-1)\sin^2\theta\cos^2\theta + \frac{1}{2(1+\sigma)} \right\} .$$

Values of E_1/E_f, E_2/E_f, G/E_f and η_0 for $k=5$ and $k=10$ are plotted in Fig. 5 (σ assumed equal to $\frac{1}{4}$). It will be seen that optimum values of η_0 occur in the region

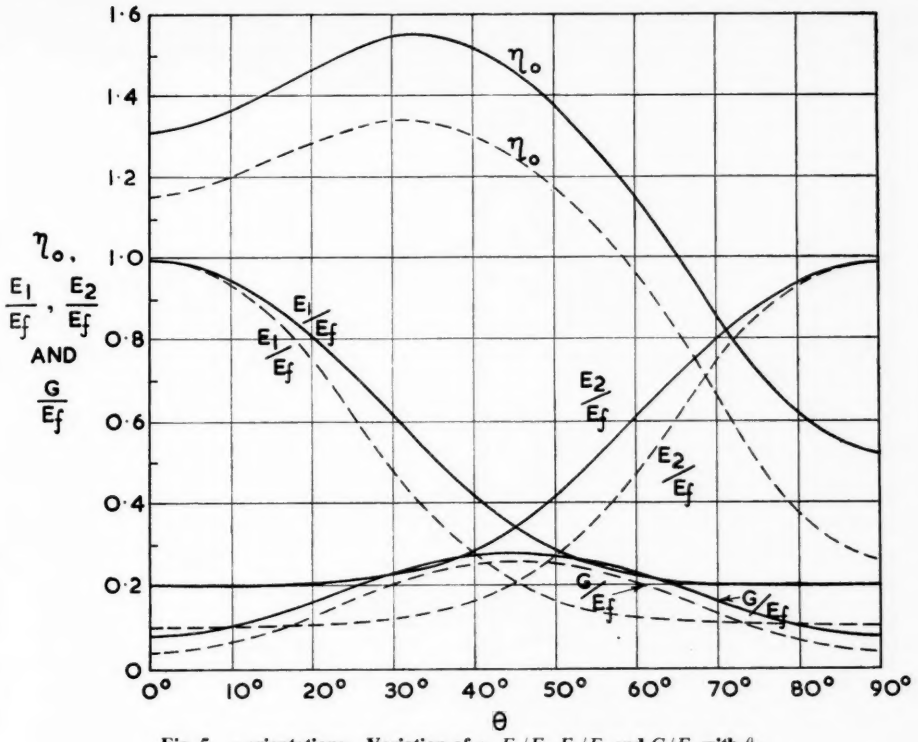

Fig. 5. χ **orientations. Variation of** η_0, E_1/E_f, E_2/E_f **and** G/E_f **with** θ.
———— $k=5$
– – – – – – $k=10$

of $\theta=30°$ and that, not only are these optimum values high, but the material is very versatile, since small changes in θ effect large changes in E_1 and G. The effects of k upon E_1, G and η_0 are plotted in Fig. 6, while η_0 for the χ-orientation and the uni-axial normal orientation are compared in Fig. 7. Here it will be seen that η_0 is greater for the χ-orientation for all values of k less than about 28, that is to say for most practical values. These curves indicate that the orientation enables increases in resin stiffness to be exploited much more efficiently than with the existing orientations; in fact it is hardly worth while increasing the stiffness of the continuum with normal orientations.

6.2.2. *The "Maltese Cross" orientation*

Since the effect of decreasing k is marked in the χ-orientation it may be enquired whether it is worth devoting some of the available fibres to this purpose. Working from the optimum, or near-optimum, case of χ-orientation when $\theta=30°$, a comparable arrangement may be considered where the majority p of the fibres lie at $\pm 30°$ and a minority $(1-p)$ lie at $\pm 60°$. It is clear that nothing has been lost in shear, but has anything been gained in tension?

Working first without the continuum and extending the equations of the χ-orientation, gives

$$P_1=\frac{E_f}{16}\left\{e_1(8p+1)+3e_2\right\},$$

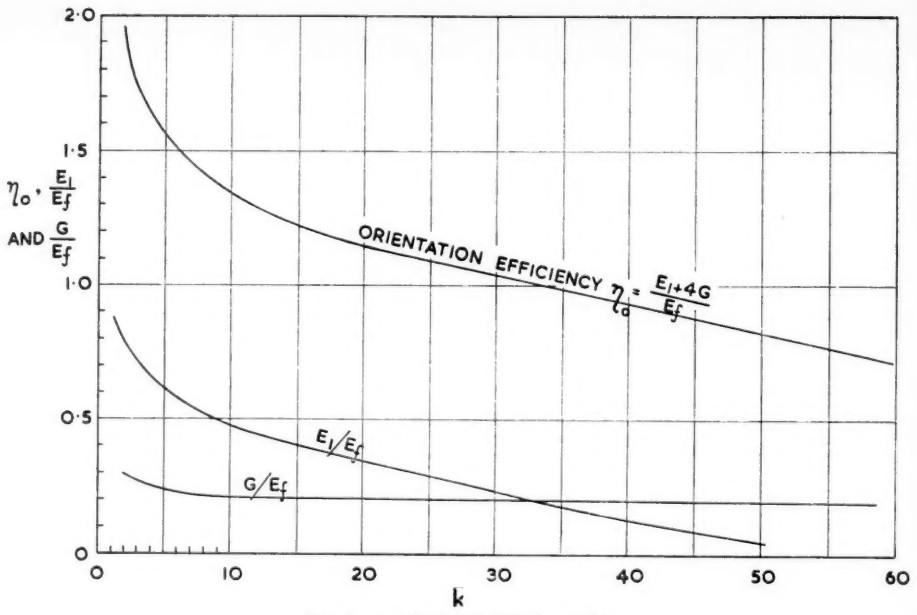

Fig. 6. χ **orientation with** $\theta = \pm 30°$.
Effect of varying stiffness of continuum upon η_0 **(orientation efficiency)** E_1/E_f **and** G/E_f.

and $$P_2 = \frac{E_f}{16}\left\{3e_1 + e_2(9-8p)\right\},$$

whence $$E_1 = 4E_f\frac{p(1-p)}{9-8p}.$$

This has a maximum value when $p = 3/4$, when

$$E_1 = \tfrac{1}{4}E_f \text{ and } G = \tfrac{3}{16}E_f,$$

so that $$E_1 + 4G = 1.$$

In other words this orientation is stable without a continuum which is not so with a χ-orientation.

Introducing the continuum with Young's modulus E_f/k, Poisson's ratio σ, gives

$$P_1 = \frac{E_f}{16k}\left\{e_1[(k-1)(8p+1)+16] + e_2[3(k-1)-16\sigma]\right\}$$

and $$P_2 = \frac{E_f}{16k}\left\{e_1[3(k-1)-16\sigma] + e_2[(k-1)(9-8p)+16]\right\},$$

so that $$E_1 = \frac{E_f}{16k}\left\{[(k-1)(8p+1)+16] - \frac{[3(k-1)-16\sigma]^2}{(k-1)(9-8p)+16}\right\}$$

Whence

$$\frac{\partial E_1}{\partial p} = 8(k-1) - \frac{8(k-1)[3(k-1)-16\sigma]^2}{[(k-1)(9-8p)+16]^2},$$

so that for the maximum value of E_1,

$$p = \tfrac{3}{4} + \frac{2(1-\sigma)}{k-1}.$$

This expression has anomalous values (>1) for very low values of k which may be due to the assumptions made in introducing the continuum, otherwise

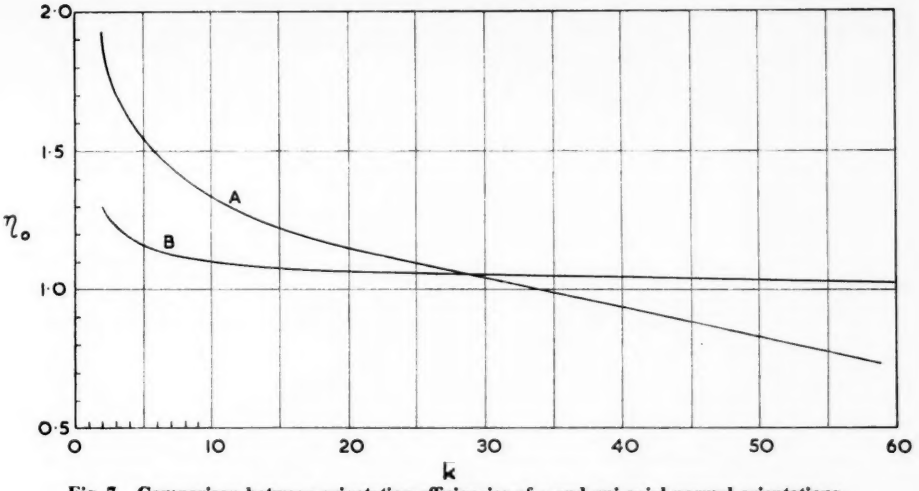

Fig. 7. Comparison between orientation efficiencies of χ and uni-axial normal orientations both at optimum orientation.

A. χ orientation with $\theta = \pm 30°$

B. Uni-axial normal orientation with $\eta = 2$ (S.D. 36°)

the values obtained are plausible. For $k=20$, for example, $E_1 = 0.356\,E_f$ and $G = 0.20\,E_f$, so that $\eta_o = 1.156$, a value almost identical with that for the χ-orientation. In other words nothing is gained or lost by this orientation as compared with the χ-orientation. On the other hand the orientation is of some interest as showing that nothing is lost by "cross-banding" parallel bands of fibres with transverse ones at 90°. In other words if crimp and twist were negligible a woven fabric could be used with a light weft, without loss of efficiency.

6.2.3. *Combinations of χ and normal orientations*

It is perhaps worth glancing briefly at the effect of combining χ-orientations with Gaussian orientations. For the optimum case of the χ-orientation when $\theta = \pm 30°$,

$$P_1 = 3\frac{E_f}{16}(3e_1 + e_2)$$

$$P_2 = \frac{E_f}{16}(3e_1 + e_2).$$

Also, for the uni-axial normal orientations at the optimum case when $n=2$,

$$P_1 = \frac{E_f}{8}(5e_1 + e_2)$$

$$P_2 = \frac{E_f}{8}(e_1 + e_2).$$

Suppose that p fibres are disposed in the χ-orientation and $(1-p)$ in the normal then, for the case when the lengthwise axes of the two orientations are parallel, the combined arrangement gives

$$P_1 = \frac{E_f}{8}\left\{e_1\left(5 - \frac{p}{2}\right) + e_2\left(\frac{p}{2} + 1\right)\right\}$$

and

$$P_2 = \frac{E_f}{8}\left\{e_1\left(1 + \frac{p}{2}\right) + e_2\left(1 + \frac{p}{2}\right)\right\},$$

so that $$E_1 = \frac{1-p}{2-p},$$

neglecting the continuum.

This clearly has a maximum value when $p=0$, *i.e.* for the all-normal case, the cases with continuum do not seem to show any exceptional promise.

When the two systems cross at right angles

$$E_1 = \frac{E_f}{2} \frac{4p^2-3p-1}{\frac{9p}{2}-5}.$$

This expression has a maximum value when $p=0.722$,

when $$E_1 = 0.31\,E_f.$$

Both of these orientations are likely to occur in practice whenever Durestos is combined with parallel bands of fibres.

6.2.4. *Conclusions upon orientations exploiting the continuum*

A χ-orientation or its equivalent, may be expected to yield values of η_0 rather better than those for a Gaussian felt at the same value of k. For example:—

	η_0	
k	*Gaussian*	χ
10	1.10	1.33
20	1.07	1.14

The use of χ-orientations, or similar ones, involves the practical achievement of sensibly parallel bands of asbestos fibres and it seems likely that the major benefit of this arrangement will be to enable a substantially lower resin content to be used. For example with Durestos, made by existing techniques, the optimum resin content is in the region of 54 per cent. (the present resin content). Laboratory samples of parallel asbestos material have given excellent results at 17 per cent. resin content, because of the much better fibre packing which results. It is not known what the optimum resin content for such an arrangement may be, but perhaps a conservative estimate is 20 per cent. This will effect a great increase in η_r, so that, assuming $k=20$ as at present:—

	Existing Durestos	*χ-orientation*
η_0	1.0	1.14
η_r	0.46	0.80
F	3.0	3.0
α_p	1.38	2.74
$\alpha = \frac{\alpha_p}{\alpha_m}$	0.54	1.08

This supposes that there is no change in k; in fact, of course, the better packing of a parallel fibre material should result in some increase in k which the χ-orientation is well placed to utilise. Besides this, major changes in the ratio of E_1 to G are impracticable with felted material but are easy with the χ-material, an effect which should be reflected in a better value for β.

Whether there are any other fibre orientations substantially more efficient than the χ-orientation is not known and might form a useful subject for further investigation. It should be borne in mind, however, that any orientation which involves scattering fibres in angle necessarily reduces the closeness of packing and so reduces η_r by an amount which may exceed any small improvement in η_0.

This discussion has excluded any consideration of possibilities of reducing the resin content of Durestos. It is known that with existing techniques the present resin content of about 54 per cent. is near to the optimum. There is some experimental evidence, however, to show that a reduction in resin content may be achieved if the resin is redistributed within the material, in other words some of the present resin is inefficiently disposed within the voids of the material; how great an improvement can be made in this way is not known, but even if a very large reduction in resin content could be made the aeolotropy of the material would still not be controllable.

6.3. Improvement by changing the shape of the fibres

The limits of what can be done using conventional fibres such as asbestos have now been discussed fairly exhaustively. In theory, at least, it is not necessary to use thread-like fibres but, for example, the use of thin plates as a reinforcement might be considered. The advantage of such an arrangement is clearly that the plates may be isotropic or nearly so, in their own plane and so have a value for η_0 in the region of 2.54 as with metals. Unfortunately, very little data seems to be available about the mechanical properties of plate-like crystals. Two materials, however, may be suggested, mica and alumina. There is no possible means of estimating η_r but it may perhaps be in the region of 0.5.

Then:—

	E_f	F	η_0	$F\eta_0$	η_r (guessed)	α_p	α
Mica	8.0×10^6	2.04	2.54	5.2	0.5	2.6	1.02
Alumina	17.0×10^6	4.54	2.54	11.5	0.5	5.75	2.26

Unless the resin content can be reduced to a low figure mica does not seem to be much more promising than asbestos. On the other hand alumina might produce a material at least twice as efficient as metals and this suggestion might be worth further investigation, although both the production of plates of alumina and the technique of gluing them together into a satisfactory material might present great difficulties.

7. CONCLUSIONS

The best all-round structural plastic at present available is Durestos. For this material α is now approaching the theoretical limit, for its present form, of 54 per cent. of the efficiency of metals. By reducing and redistributing the resin content there is some possibility of increasing the efficiency to a figure in the region of 60-65 per cent. of that of metals; it is unlikely that the material can be improved beyond this figure.

Assuming that the performance of Durestos structures is roughly equal to that of metal structures then the structural efficiency criterion β must have had a value in the region of 1.92. In other words the plastic structures, as structures, were nearly twice as efficient as their metal counterparts. It follows that it should be well worth trying to improve the efficiency α of the materials if by doing so the efficiency β of the structures is not sensibly reduced.

The scope for improvement in a felted material such as Durestos is limited and the best prospect for large improvements appears to be in the use of parallel bands of fibres disposed in some such arrangement as the χ-orientation. Such arrangements exploit the continuum efficiently, enable large reductions in resin content to be made and are very versatile in the combinations of E_1 and G which are readily afforded.

A material made on these lines promises values of α in the region 1.08, that is to say a material with just twice the all-round properties of Durestos.

Any increase in the efficiency of the material (without a corresponding decrease in density) will involve the use of thinner sections of material in a given structure, which would give a decrease in values of β. Against this, χ-orientations are much more versatile than felts, and afford a wide range of combinations of E_1 and G so

it may perhaps be considered that the two factors will offset each other in their effects upon β and that a value of $\beta \simeq 2.0$ will be maintained; in practice (by analogy with Durestos) a real value of α in the region of 1.0 might be expected. On this basis there is a hope of making structures having a weight of $1/1.92 = 52$ per cent. of that of metals.

Such a result is dependent upon the achievement of sensibly parallel asbestos bands with a lower resin content (about 20 per cent.), a matter of great practical difficulty; however, a good deal of work is being done upon the subject and some success has been achieved with small scale experiments.

It is worth remarking that, counting the various adhesives which are used, about two thirds of the weight of existing R.A.E. plastic structures consist of resins of various kinds which make a negligible direct contribution to the overall strength and stiffness of the structures, while the fibres themselves are not disposed in the most efficient manner. It will, therefore, be seen that a target of half the weight of existing plastic or metal structures is not unduly ambitious, but this seems to be about the limit using existing fibres and in the light of present knowledge.

Looking farther ahead and for still larger weight reductions, either fibres must be devised which are substantially stronger and stiffer than asbestos or else a complete change must be made in the shape of the reinforcing particles.

There exists at least the theoretical possibility of using alumina plates which should enable a material to be made about twice as efficient as the best that can be foreseen using asbestos fibres (and about four times as good as Durestos). The effect of such a material upon structure weights might be so revolutionary that it may be worth expending some effort in trying to solve the practical problems involved. It should be emphasised, however, that the difficulties of developing such a material would be very great and that the project would necessarily be a long term one.

Acknowledgment

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CORRESPONDENCE

DESIGN PROBLEMS FOR INTERCEPTOR FIGHTERS

It is always interesting and useful to the designers of a product to have the comments of the users of that product, and the more so when they include reasoned comparisons with the results of different approaches to the same problems. Lt.-Cdr. Bailey (June 1952 JOURNAL, p. 438) evidently speaks from first-hand operational experience of both the aircraft he has chosen to illustrate his arguments, but it would appear that in some respects he is not completely aware of present-day practice at the design end of the business.

Most of us have not so far had the advantage of obtaining authentic figures for "the enemy aircraft," but assuming the all-up weight quoted of 10,000 lb. is correct, only a very small part of the difference of 6,000 lb. between this and "the U.N. aircraft" could be accounted for by a difference in stressing factors. A typical analysis of the structure weight of a jet fighter would be:—

Item	*Per cent. all-up weight*	*Primarily determined by*
Wings: spars	6	*g* factor and all-up weight.
skin covering	5	Diving speed.
remainder	4	Linear dimensions.
	15	
Tail units	3	Dimensions and diving speed.
Fuselage	7	Dimensions and diving speed.
Undercarriage	5	All-up weight and dimensions.
	30 per cent.	

Thus, only one item, averaging about 6 per cent. of the all-up weight, is directly affected by the stressing factors used, and if these were reduced in the ratio 8:12 for the larger aircraft, *and nothing else changed*, the all-up weight would be reduced by less than 500 lb. In practice other things *would* be changed, *e.g.*, the wing area and span may be reduced to keep the same wing loading, some reduction in fuel may be made (if the allowance is based on flight conditions affected by aircraft weight and not simply on engine consumption at a fixed rating), and a progressive reduction in aircraft weight and size obtained, but the total saving is most unlikely to exceed 1,000 lb. On the structural side a more powerful effect would be given by reduction of "design diving speed" which to a greater or lesser extent affects more components, but any appreciable reduction in design speed would be expected to be reflected in an increased number of structural failures in combat, and as these have not been reported as observed one must probably look elsewhere for an explanation of the enemy's lighter weight.

It is true that the axial engine is usually rather heavier, but one of the reasons for its adoption is reduced fuel consumption, so that on these relatively short endurance aircraft the sum of (engine plus fuel) is likely to be about the same. The most likely cause of the weight difference is in the weight of military load and equipment carried. This can affect the final all-up weight in several ways; directly on some items of the main structure, also by requiring subsidiary structure for its own mounting, by requiring an increase in the linear dimensions and hence weight of (usually) the fuselage, and indirectly because any increase in either weight or size of the aircraft usually means that more fuel is needed, which in itself produces a further weight increase. If the equipment happens to be radio or radar there is another effect, in that it will mean a still further increase in the weight of the already large electrical power supply system.

Lt.-Cdr. Bailey's plea for reasonably low wing loadings is a sound one, since the effect on manœuvrability, particularly at high Mach numbers, can be very pronounced, but his point (*b*) on loss of thrust is not made clear.

Most designers would join in deploring the increasing complexity of fuel systems, but with jet aircraft the demands are so great that every available corner has to be used for fuel. It is very tempting to fill up most of the fuselage with a single large cylindrical fuel tank, only to find that the remaining spaces in the fuselage and wings are altogether the wrong shape for the numerous large rectangular "black boxes" now deemed indispensable for finding and hitting the enemy. A gallon of fuel will go into a variety of shapes of that capacity, but a piece of equipment of 1 ft. cube will never fit into a wing 9 in. deep! Also, the c.g. position of the aircraft must not alter appreciably with consumption of fuel; most of the usable wing space is near the c.g., but a tank near the nose of the aircraft will have to be balanced by one near the tail, whereas a radio set in the same position will be there all the time.

Although the "customer" demands a Type Record giving the results of stress calculations on the main components only, this does not mean that these are the only ones that are checked. Even those minor parts for which no exact load can be estimated, are carefully

scrutinised to ensure that every ounce of material is used to the best advantage. It is probably true that the performance of plastics (except as transparencies and for jointing) for constructional uses has been disappointing, but there are nevertheless some 100 " Aircraft Standard " parts such as hand wheels in use in the British Aircraft Industry.

Lt.-Cdr. Bailey is grossly unfair to the aircraft being produced for his own Service in suggesting that their bomb-carrying capacity will be in any way inferior to American counterparts. The correct figure for the strike aircraft he mentions is a bomb load of 50 per cent. of the normal service load, and the aircraft has been publicly demonstrated with a considerably greater load. It is to attain the objective of high loads for less fuel than is needed for jets that the development of the turbo-prop. aircraft for Naval use has been most persistently pursued in this country.

The advantages of after-burning for thrust boosting and keeping down the size of interceptor fighters are rather under-rated; far from becoming less effective at high altitude the reverse is true, *e.g.*, a 30 per cent. increase at static sea level becomes 45 per cent. at 30,000 ft. and 500 knots.

The most likely reason for the use of steel as a spar boom material is not specifically stated, namely that the higher density enables a steel boom of the required area to be more compactly and economically disposed in a thin wing than the larger area of aluminium alloy, and it is in this way that weight can sometimes be saved in spite of the direct tensile strength of steel being lower in proportion to its density than for the best light alloys.

In general one has the impression that the author does not give due credit to designers for " weight consciousness." In Great Britain, at least, all available information on means of correctly estimating and saving weight on every part of an aircraft and its equipment is freely exchanged between firms. Rather it is in the specifying of the equipment for fighters that the greatest savings are to be obtained; no single item should be carried that is not absolutely indispensable, and even then it must be certain that the advantages gained from it are not largely offset by the cumulative reduction in the performance of the aircraft, which for the interceptor fighter most of all will always be the deciding factor.

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WESTLAND AIRCRAFT LTD.

Lt.-Cdr. Bailey, in his interesting and provocative paper, has over-simplified many of the problems that he considers. He suggests that British Service aircraft can be considerably improved by revision of conventional design and constructional methods. Such improvement is naturally possible but I believe that he exaggerates its relative importance and that greater effect could be obtained by adjusting Service requirements—particularly, for Naval aircraft, those dealing with equipment.

The author's experience of flying carrier-based aircraft gives weight to his opinions. Unfortunately the paper gives an overall impression that is, I believe, completely erroneous.

In paragraph 3, it is suggested that most of the difference between all-up weights of otherwise comparable Allied and Soviet aircraft (16,000 to 10,000 lb.) is due to a loading difference of 12*g* to 8*g*. Soviet aircraft can only be designed for a sea level loading of 8*g* if they confine their more energetic manœuvres to high altitude. Otherwise, many aircraft will return from combat suffering permanent deformations, and a change in flying characteristics, etc.—if they avoid complete break up. Even if these figures are accepted, and the fact that stiffness rather than loading designs much of modern fighters is neglected, the resultant weight reduction is small. Wing and fuselage torsional material is required to carry rolling and yawing loads, so that only wing and tailplane spars and root ribs, and fuselage bending material have to be considered. These parts account for about 6 per cent. of the structure weight, or 2 per cent. of the all-up weight. If the same power plant is kept and the " snowball " effect is included[1] this will result in no more than 1,000 lb. reduction in the weight of our postulated 16,000 lb. fighter. It would seem that the further reduction of 5,000 lb. can only be obtained by removing 1,500 lb. of equipment and associated structure. The total weight of equipment in a 16,000 lb. fighter will be about 3,500 lb.[2]

In paragraph 2, it is stated that there is little scope for improving Mach number limits of Service fighters beyond 0.93, or for Delta wings 0.95.

Early swept wing aircraft were unsatisfactory as a gun platform above about 0.85. The improvements that have been made since then will continue, as various methods are adopted. These cannot be listed here, but the reduction of thickness chord ratio which was quoted is only one of a number of changes—and will not have the overwhelming effect suggested. For example, consider the weight penalty due to a reduction of wing thickness from 10 per cent. to 7 per cent. Such swept wings and tail surfaces will be designed largely by stiffness requirements and the working structure will vary roughly as $(t/c)^2$ [3]. For a 16,000 lb. aircraft this structure weighs roughly 1,000 lb. and the reduction in wing and tail thickness increases this

to 2,000 lb. This is equivalent to a loss of 125 gallons of fuel. Assuming that satisfactory high lift devices are maintaining $C_{L\max}$ in both cases, the penalty is large, but it does not have the overwhelming nature suggested by Lt.-Cdr. Bailey.

At least it can be said that no arbitrary limit can be set to the operation of aircraft as a gun platform, continual improvement should occur.

The importance of weight saving, as mentioned in paragraph 4, cannot be over-stressed, but the suggested methods are of limited application.

If, as was suggested, one fuel tank is employed, all fuel can be lost after one strike on the aircraft. For this reason four or five separate tanks seem to be required. Also a large head of fuel builds up during arrested landings with tanks of considerable length—or during rolls with tanks of great spanwise extent, and this increases the weight of containing structure. The author is right in drawing attention to the complexity and weight penalty of numerous tanks, and I would add that containing structure rapidly increases in weight as bag-type tanks depart further from the ideal sphere.

Less than 5 per cent. of the structure by weight is not stressed, on a typical fighter aircraft. I agree that larger technical staffs should result in reduced structure weights, but this will result mainly from more thorough examination of structure in the Project Design and Drawing Office stage, a better knowledge of loads, based on improved flight data, and extended structural tests, etc.

Similarly, weight saving will result not by using reinforced plastics alone, but by such other things as machined skin panels, sandwich construction, Reduxing, large forgings, magnesium, titanium, high grade steel and the like—to an extent that only experience can indicate. There is no panacea.

The comparison of bomb load as a percentage of normal service load, which completed paragraph 4 is meaningless. Almost any percentage specified can be supplied. If the Service concerned wishes to have the proverbial kitchen stove among their aircraft's equipment, they should use it in some destructive manner in place of the discarded bombs.

The comparison between rocket motor and after-burning cannot be pressed here since fuel consumption at various altitudes, weight and complexity of equipment and installation possibilities, cannot be quoted. Possibly the comparison can only be made by studying two aircraft projects of comparable performance. If we had to operate an aircraft at about 70,000 ft. only (say) then rocket boost would be superior, but with present operational altitudes no such clear advantage exists.

I would have expected Lt.-Cdr. Bailey to discuss such matters as:

(1) Deletion of aircraft undercarriages (flexible deck).

(2) Raising of landing and launching speeds by improvements in carrier gear.

(3) Overside aircraft lifts—these combined with aircraft stowage trolleys might save the weight and complexity of wing folding.

(4) Small expendable aircraft versus two-crew aircraft—at the price of a destroyer.

(5) The use of specialised high altitude aircraft, limited in their manœuvrability at low altitude by airframe flexibility or lack of strength.

(6) The removal of some equipment to give an improved aircraft-pilot combination, considered as a single weapon.

Since this last point is an important one, I quote the American Vice Chief of Air Staff who was recently reported as saying[4]: "This country has always overbuilt its aircraft. They are too heavy. We have to get into that and cut the overall weight of equipment down to get performance. The safety factors we have built in . . . we have overdone."

Also[5]: "Experienced F.86 combat pilots believe that close to 2,500 lb. of equipment can be stripped out as well. As one put it: 'We have got to stop building training aircraft and start making combat airplanes.' A lot of the safety features for peacetime flying become combat hazards by adding to airframe weight."

I wish to acknowledge the assistance of colleagues. The opinions expressed are my own. (I do not write as a member of an aircraft firm.)

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REVIEWS

The following are reviewed:—

Powder Metallurgy
Protection and Electro-Deposition of Metals
Bibliographical Survey of Flow through Orifices and Parallel-Throated Nozzles
Air Power Key to Survival
Theory and Technique of Soaring
Elements of Statistics
Typical Helicopter Performance Calculations
Aircraft Maintenance
Radio Astronomy
Stuka Pilot

POWDER METALLURGY. Volume 9. C. J. Leadbeater and Others. H.M. Stationery Office 1952. 159 pages. Illustrated. Index. Price 18s. net.

In the ceramic arts an advanced stage has been reached in creating shaped, more or less solid pieces, of material by bonding powders together and heating the shaped compress. The development of this art has been spread over many thousands of years, but the corresponding techniques for metals and alloys are of fairly recent introduction, mostly during the period between the two World Wars. A great deal has been learned of the techniques of producing shaped articles: probably much less is known of the basic science that is involved. Only quite recently has it been possible to attach the problem scientifically by applying thermodynamic theory to the adjoining together of discrete particles of alloys by heating them to temperatures which do not induce total melting.

It is probable that in the period between the wars the employment of tungsten carbide for tipped tools and cognate applications provided the greatest single urge to advancing the art of powder metallurgy, even though the free metal in such tools was present only in subsidiary proportions. But more recently the needs of war provided a powerful stimulus to the development of powder metallurgy methods for making large numbers of smallish components. These ranged from moulded magnets, through piston rings, to driving bands for ammunition, and to numerous items of equipment for small arms and for motor vehicles. Almost every metal has been worked on, from the highly refractory—like tungsten—to such low-melting-point ones as tin. Quite a notable proportion of the success attained in the recent work on titanium is attributable to the production of dense bars, from titanium powder, by the standard methods of powder metallurgy.

These various aspects of the subject are reflected in the contents of this volume of Research Reports. The ten researches that are dealt with date from the years 1943 to 1948 and all but two (which are R.A.E. reports) are the work of A.R.D.Met. They cover a wide field: such relatively basic matters as surface energies of metals or alloys, the mechanism of sintering, and flow under pressure appear at one end of the scale. Methods of preparing powders, the properties of powders, the influence of variations in particle size, shape, or structure, are attacked from various angles: while the examination of numerous components made by sintering metal powders—including many war-time German products—come at the other end of the list. The problems and possibilities of powder metallurgy are of interest in many branches of industry and most engineers will find in this volume much that is worth careful study.

PROTECTION AND ELECTRO-DEPOSITION OF METALS. L. F. Le Brocq and Others. H.M. Stationery Office. 350 pages. Illustrated with Index. Price £1 10s.

Truly, a volume of rather heterogeneous research reports is one of Charles Lamb's *biblia abiblia*. Written by divers authors over a fairly long period of years, presenting factual accounts of investigations varying greatly in breadth and depth, many undertaken on problems which appeared to be important once upon a time, the collection of papers making up this volume is difficult to summarise or discuss. It is published as one of a series of Selected Government Research Reports, " primarily for the benefit of British industry."

This publication contains twenty reports in its first section, headed " Protection of Metals," and thirteen in the second, devoted to " Electro-Deposition of Metals." The scope is narrower than these headings might suggest. Seven of the first twenty reports deal with aluminium alloys, nine with magnesium and its alloys, three with steel, and the odd one with the permeability of organic coatings. Most of the work on aluminium alloys focuses either on features of the processes for anodic oxidation or on the testing of different materials treated by these processes. The magnesium researches have two principal interests; first, the different types of chromatic-dip treatments, notably that developed at R.A.E., and, second—broadly—the effects produced on corrosion resistance either by impurities present in low proportions or by surface contamination.

In the second section seven reports deal with aspects of the chemical analysis of plating solutions, four with testing the efficiency of adhesion of coatings, one with the behaviour of

a cladding of relatively low purity, and one with selenium coatings on magnesium. The majority of the researches reported in the first section were made at R.A.E.; of these in the second section most were conducted by A.R.D.Met. The earliest reports are dated 1939, and the latest 1947, the majority belonging to the years 1944 to 1946. Apparently the reports are now issued, in full, in their original form with all the tables of data quite complete and illustrated as when first put out. No reader could complain that data are being withheld.

All the work reported in this volume was carried out in a painstaking and thorough fashion. For those undertaking further research on the topics considered in this volume, produced extremely well and sold at a moderate price, it is likely to be very valuable. Nobody is likely to read it; but many may be glad to possess it for reference. The opinion may be hazarded that those branches of British industry interested in the operations which prompted these investigations are already well acquainted with the researches and their outcome. It may be regretted therefore that the easy way of publication—for authors but not for readers—has been taken. Surely, a more acceptable volume would have emerged if the material, set out here at length, had been summarised and the new knowledge resulting from the researches been indicated clearly. The essence of the work might then have been offered in a readable form and, possibly, the constructive comments made on the reports when first issued might have been incorporated for the benefit of new readers.

A Bibliographical Survey of Flow Through Orifices and Parallel-Throated Nozzles. T. H. Redding. (B.S.I.R.A. Research Publication, M.9.) Chapman & Hall, London 1952. 197 pages. Figures. Appendix. 32s. 6d. net.

A valuable reference work and guide for those engaged on investigations relating to fluid flow through orifices and parallel-throated nozzles, with emphasis on the application of these devices for the measurement of rate of fluid flow. Mr. Redding is a senior member of the research staff of the British Scientific Instrument Research Association whose Council has encouraged him to publish his work in book form in order to permit the widest possible availability among interested technicians.

The bulk of the book comprises a carefully selected and arranged bibliography relating strictly to the field of orifices and parallel-throated nozzles. Reference works cited are classified into 16 different subject categories, including historical and general treatments, investigations on the flow of liquids and of gases through pipe and end-cap orifices and nozzles, free discharge of liquids and of gases, the theory of adiabatic compressible flow of gases through orifices and nozzles and critical flow phenomena.

A special section is devoted to codes of metering practice and another to special methods of computation and the application of discharge formulæ to the solution of problems. Publications relating to the metering of fluids with pulsating flow are grouped in one section. Other sections contain bibliography pertaining to the use of orifices and nozzles for testing and calibrating positive meters, and to the installation, construction and operation of metering orifices and nozzles. Applications of the principles of dynamic similarity and dimensional analysis to orifice and nozzle flow, and investigations on the hydrodynamics field set up by flow through orifices and nozzles are reviewed in the two final sections.

All bibliographical references given include abstracts.

The main bibliography is preceded by a valuable technical Introductory section which gives this book a special value and substantially contributes to its usefulness as a reference work. In this the distinguishing features of orifices and parallel-throated nozzles are discussed, and the broader aspects of their use for metering purposes is considered in an instructive manner. A stabilised form of terminology relating to the subject is treated in an Appendix, to which reference is made in the Introductory section. The scope and contents of the bibliography are introduced clearly and concisely.

Orifices and parallel-throated nozzles are being used on a large scale in the Industry for the measurement of the rate of flow of liquids and gases and this book will be, to quote the author in his preface, " of use and interest both to research workers and to a large body of technologists who are, from time to time, confronted with problems relating to the measurement of fluid flow."

Air Power Key to Survival. Alexander P. de Seversky. Herbert Jenkins 1952. 328 pages. Illustrated. Index. 21s. net.

In this brilliantly written and comprehensive exposition on the strategy of air warfare Seversky examines the fundamentals of a world struggle where a thousand million men would be concentrated by the U.S.S.R. in an invincible surface force against which there could be no hope of victory for an opposition comprising an equitriphibious composition of Army, Navy,

and Air Force, and is forced to deduce that the entire design of present preparations is doomed to failure. It is a conclusion which will disturb and shock, whatever minor fallacies or omissions of argument each reader may discover for himself.

Although the entire conception of the book is directed towards global warfare nevertheless it is written from an intensely American viewpoint. Essentially a powerful plea addressed to American citizens, it has lessons for all to read. Though it scarcely mentions Great Britain, other than to premise it is a useful forward base, Seversky makes an initial and clear analogy with the *Pax Britannica*, during which the world enjoyed a hundred years of comparative peace and modern civilisation came to fruition. England, throughout that time, without paying the penalties of full militarisation, was able to dominate the world by concentrating on decisive sea power, for without being gigantic it had only to remain just sufficiently superior to the sea power any other combination of countries could provide. The mere existence of quick striking ability became a global peace insurance. The basis of Seversky's thesis is that American air power could and must exercise a parallel function to-day, for an enemy would then be forced to fight on American terms in a medium where a natural superiority was too obvious to be questioned or ignored.

The logic is difficult to contravert, however much the traditionalist may argue that armies and navies can always secure bases suitable for relatively inexpensive, medium-range aircraft which would bring them within striking distance. The fact that it costs vastly more to provide such bases than build aircraft of adequate range gives Seversky the overwhelming conviction that war must be fought from the United States itself, and his challenge is that this implies relegation of all older methods of attack, and dependence instead on giant armed bomber aircraft having a potential radius of 5,000 miles.

He bases this viewpoint on the prodigious industrial capacity of the U.S.A. which far outweighs that of the U.S.S.R., and contends that if the greater part of this productive energy were devoted to an interglobal "Army of the Air" then enemy war potential could be destroyed at its source.

At this very moment in history, warns Seversky, the U.S.A. is launched on an incredibly profligate strategy, suicidal in its waste of substance on superfluous weapons, while the additional attempt to revitalise European self-defence can have so thin an effect against Russian hordes as to be worthless. It is the purpose of his book to expose the fallacies of present policy, and prove that Air Power is the key to survival when " the permanent co-existence of two violently opposed social and moral systems has become impossible. Either one ideology will succumb to the other through persuasion, infiltration, and contamination—or a military showdown will become unavoidable. But whatever history has in store, humanity must one day achieve a world under law, when the universal disarmament of which all decent men dream will be a fact. Until then, while striving for peace, we must prepare for victory if the peace is broken."

THEORY AND TECHNIQUE OF SOARING. John Kukuski. Pitman, London. 1952. 180 pp. 180 figures. 25s. net.

Soaring is the art of delaying the victory of gravity. The art has progressed to such an extent that men have climbed more than 45,000 ft. and have flown more than 500 miles in a day without recourse to mechanical assistance except for a few moments at the start. These remarkable achievements have been made possible by designers and pilots with a wide knowledge of the sciences connected with aeronautics—of aerodynamics and meteorology, of aircraft structures and instruments—so that those who wish to become proficient must acquire some knowledge of these varied subjects.

Mr. Kukuski has succeeded in producing a worthy addition to the gliding literature. The first third of the book is devoted to relevant aspects of meteorology, mostly acceptable to all meteorologists but containing some of the author's original ideas, particularly on " thermal " formation. The next third discusses glider instruments, the aerodynamics of gliding flight and the loads occurring on the aircraft. The author's treatment is sound but the subjects covered are so vast that the reader who wants more than a superficial knowledge will have to go to the many books dealing with these aeronautical subjects. The remainder of the book deals mainly with technique of launching, soaring and landing. The chapters on navigation and instructing are so short that they hardly merit inclusion and the chapters on aerobatics and parachutes could well have been shortened so that some notable omissions could be made good. There are 180 excellent line drawings but not one photograph to illustrate a most photogenic subject. No mention is made of the international system of glider badges, such as the " Silver C "—nor of the national and world achievement of glider pilots. The inclusion of these would have broadened the appeal of the book.

Mr. Kukuski's book should be read by all interested in gliding and it will surely stimulate those arguments and discussions which ensure progress in the art.

ELEMENTS OF STATISTICS. C. G. Lambe. Longmans, Green & Co., London. 1952. 112 pp. Diagrams and Tables. 8s. 6d. net.

A recent correspondent to *The Times* claimed to have shown that, for success in a football pool, the pin-sticking technique is at least as effective as expert forecasts, studies of form and permutations. This statistical result undoubtedly would find no favour with the average pool investor who in other things demands, in quantity, standards of quality unattainable without statistical methods. But if the man-in-the-street can be choosey in his application and use of statistical method, the scientist uses it as a probe into physical phenomena which is of all probes, probably the least affected by environment. It is this property of objectivity in statistics which, with its (intrinsic) ability to deal with the very large numbers which are typical of modern life, makes it almost indispensable to the critical observer or creator in the physical world.

Dr. Lambe sets out to teach the application of the simpler statistical results to the study of observations. This technique is exposition and example, not necessarily in that order; and the result is an interesting book which should give the intelligent beginner few difficulties. His choice of a profusion of numerical examples in favour of analytical demonstrations is surely right in the circumstances, and the only weaknesses are the occasional purer mathematics which appear to have been put in for the rather more mathematically minded reader.

The development of the subject is a usual one. Discontinuous frequency distributions and the definition of the various parameters of a distribution serve as an introduction, and continuous distributions come next. The order of this procession is always arguable, but here it is right. The empirical approach is rather overdone in a very short chapter on probability. The binomial and Poisson distributions chapter is followed by one on the normal distribution; here there is a possibility of the uninstructed reader being confused at these various distributions whose close interdependence could well have been shown more clearly. The important correlation theory is rightly given the longest chapter, followed by analysis of and theory of errors in observations. The book ends with an interesting chapter on quality control.

A straightforward style and interesting material are helped by good printing and layout. Altogether, the book is a thoroughly good introduction to practical statistics, and can be well recommended, especially to the beginner.

TYPICAL HELICOPTER PERFORMANCE CALCULATION. R. J. Harris, L. H. Sloan and K. W. Ulrich. Rotorcraft Publishing Committee, Morton, U.S.A. 1952. 43 pp. Diagrams. $1.25.

This is the second volume of a series on the theory of rotary wing aircraft. The series began when notes of lectures given by W. Z. Stepniewski to workers at the Piasecki Helicopter Corporation in 1947-8 were expanded and revised by Mr. Stepniewski, printed by multilith and issued by the specially formed Rotorcraft Publishing Committee in 1950 under the title "Introduction to Helicopter Aerodynamics."

The Committee promised then that other volumes would be prepared and the booklet now published, Volume II, is in response to a demand for a "worked example." A single-rotor configuration is chosen and the equations developed in Volume I are used to calculate the performance characteristics in vertical and forward flight.

In all performance calculations the art is in making reasonable assumptions—anyone can solve an equation. The helicopter equations themselves have been developed only as a result of fairly sweeping assumptions so that the authors rightly simplify their calculations whenever possible. The test of a performance calculation is whether it gives the results measured in flight and there is every reason to believe that the methods presented here are sound.

Further volumes in this series will be awaited with interest.

AIRCRAFT MAINTENANCE. D. J. Brimm and H. E. Boggess. Pitman, London. 1952. 475 pp. Illustrated. 40s. net. *Second Edition.*

The first edition of this book was published in 1940. The major change in the new edition is the addition of a section on Aircraft Hydraulics, consisting of 40 pages, which replaces the two or three odd pages on this side of the subject contained in the first edition. This has been done—quite justifiably in the light of recent aeronautical progress—at the expense of the Section on Aircraft Woodwork, which has been reduced to almost half its original length. Apart from this, the matter dealt with is much the same as before, except that here and there, where necessary, it has been brought up to date by cutting out old material and adding new. The contents are thus now divided into five main sections: Aircraft Woodwork, Aircraft Metal Work, Aircraft Fabric Work and Finishing, Rigging, Handling and Maintenance, and Aircraft Hydraulics.

This book is intended primarily for the student-mechanic and as a reference book for licensed mechanics and is essentially a practical work. To write such a book adequately and to explain lucidly such things as the correct way to handle tools and how to effect repairs, is no easy task, and the authors are to be congratulated on doing the job well.

A book recommended to the student-mechanic.

RADIO ASTRONOMY. Bernard Lovell and J. A. Clegg. "Frontiers of Science" series (Ed. B. Lovell). Chapman & Hall Ltd., London. 1952. 238 pp. 8 plates. Figures. 16s. net.

Approximately the first third of this excellent and comprehensive little book is occupied by a concise summary of the fundamentals of astronomy, radio and radar. The authors, both of whom were prominent in the development of radar, then discuss the synthesis of all these subjects into what is no less than a new and exciting science—radio astronomy.

Although Jansky, as far back as 1931, discovered that radio waves were reaching the Earth from outer space, radio-astronomy as such is less than ten years old. The pre-war investigations, notably those of Appleton on radio reflections from the ionosphere, led to the wartime use of radar for aircraft detection and other purposes, and now in turn the techniques developed for these practical ends have been re-applied as a powerful tool in the service of pure science.

The "radio-astronomers" began by studying meteors by radar methods, measuring their velocities, numbers, and trajectories more accurately than is possible by any other means. Radar echoes from the Moon were also obtained, and Drs. Lovell and Clegg discuss the possibility of extending these investigations to cover the other planets, when more advanced equipment becomes available. Of distinctly stimulating interest, to those who envisage the development of flight beyond the atmosphere, is their remark: "—a body the size of an average aircraft could be detected at distances further away than the Moon."

The study of the random radio waves (or "noise") emitted by our Sun led to the further discovery that similar radiation comes from elsewhere in the Galaxy, and (more recently) even from extra-galactic sources, such as the Andromeda Nebula (another galaxy like our own). Attempts to pin-point these sources have shown them to be mainly unassociated with visible stars, and most unlikely to be located merely in the very diffuse interstellar dust or gas. The scientists concerned now believe that a hitherto completely unknown type of heavenly body—the "radio stars"—is involved, and latest researches have shown that there are about as many of these as there are visible stars. Ryle, of Cambridge, has suggested that the same processes which generate the radio transmissions from these mysterious cold "stars" may also be responsible for the previously inexplicable primary cosmic rays.

Clearly these new techniques are on the verge of creating new advances in the fields of both cosmology and fundamental physics. Realising this, Manchester University has established a Chair of Radio Astronomy, now held by the pioneering Professor Lovell, and it was recently announced that this year the Government would contribute half the cost (over £300,000) of a new and improved 250 ft. diameter steerable radio telescope, at the Jodrell Bank Experimental Station from which most of the new knowledge has come.

Members should read this book, both for its description of what is truly one of the new "frontiers of science," and for its example of the intricate inter-relationship between all classes of technical research and development work. From wartime aircraft radar has come a completely new technique for increasing our knowledge of matter and the Universe—from that will come—what?

STUKA PILOT. Hans Ulrich Rudel. Euphorion Books, Dublin. 1952. 259 pp. Photographs. 12s. 6d. net.

This is a book well worth reading if only because it is one of the few in English written by a German pilot of World War II.

"Stuka Pilot" is best described as a war diary of the most outstanding German pilot of the war, Rudel, who completed the incredible total of 2,530 operational flights and was credited with the destruction of over 400 Russian tanks.

Rudel as an author is no Saint Exupéry and his account is a purely factual description of events. The only venture into philosophy is a short speculation on the effect of Communism on European civilisation and on the folly of the British, American and French in not agreeing to an armistice with Germany to resist the Russian invasion of Europe in 1944.

The book describes primarily the author's dive-bombing and tank-busting activities on the Russian front. Indirectly it gives an interesting account of the general organisation and operational methods of the Luftwaffe. It might have been expected that a pilot of Rudel's experience would have commented at some length on his aircraft. Unfortunately, or otherwise, this is not so and one is left with the feeling that the author regarded his aircraft as being merely a means of transport for himself and his guns, the only passages in the book of direct interest to the aircraft designer being those connected with the effects of extreme cold on the engine and armaments.

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